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(54) **HIGHLY DURABLE SUPERHYDROPHOBIC, OLEOPHOBIC AND ANTI-ICING COATINGS AND METHODS AND COMPOSITIONS FOR THEIR PREPARATION**

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(58) **Field of Classification Search**

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(57) **ABSTRACT**

Highly durable hydrophobic, oleophobic, and anti-icing coat-  
ings and methods of their preparation and use are described  
herein.

**32 Claims, 17 Drawing Sheets**

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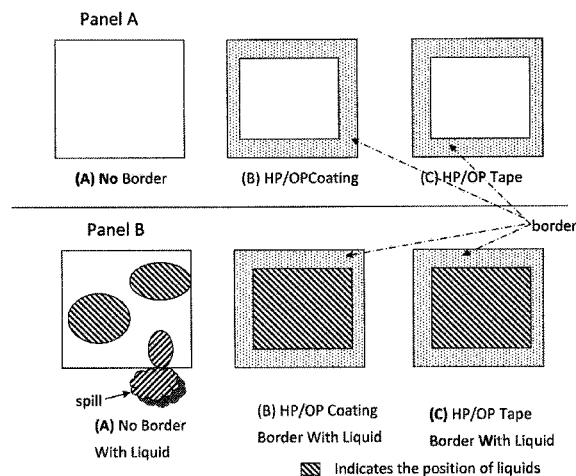
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Figure 1

Figure 1 Panel A

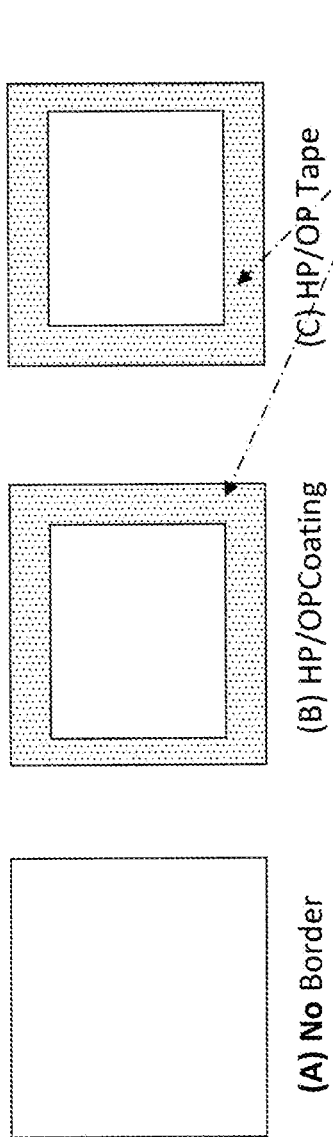


Figure 1 Panel B

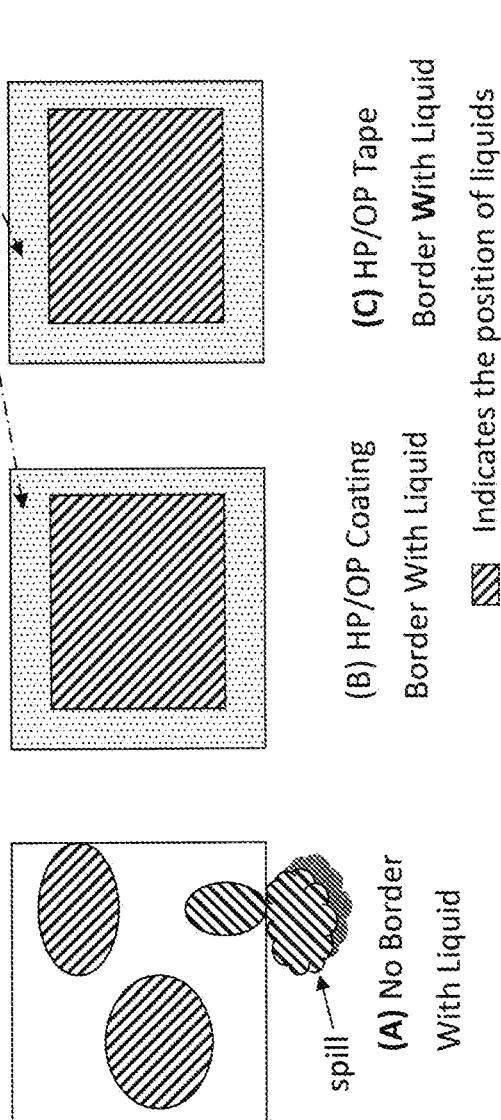


Figure 2

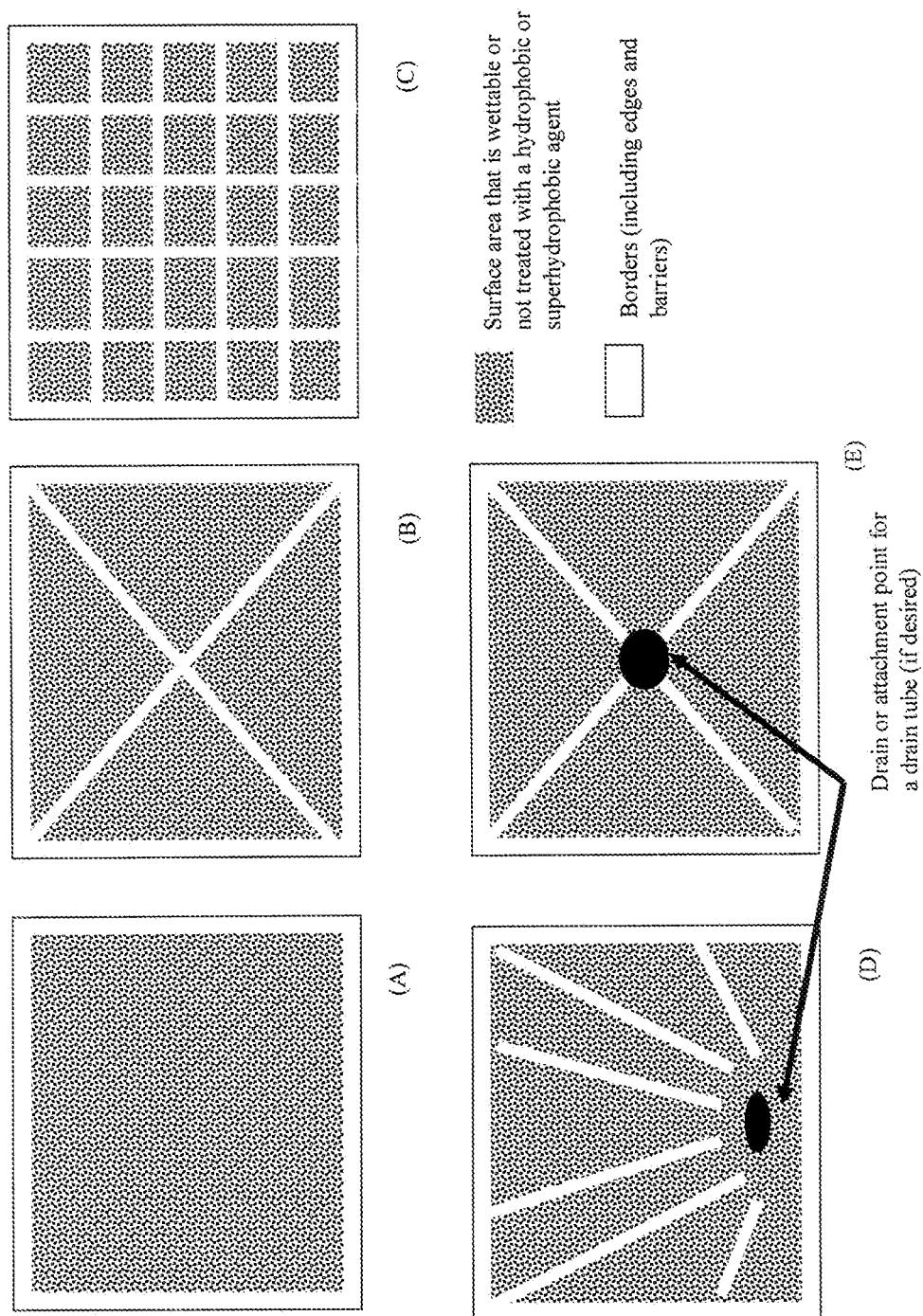


Figure 3

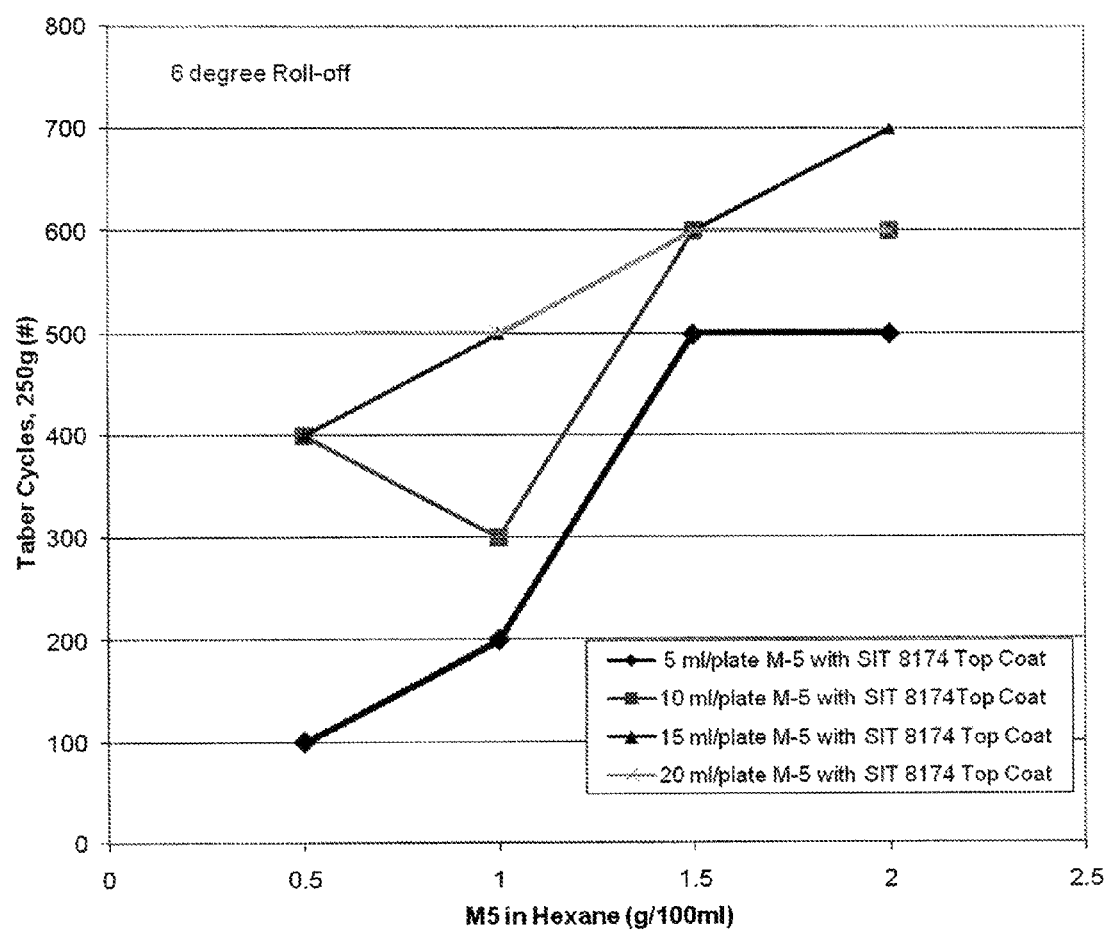


Figure 3: Taber cycles as affected by concentration of M5 and the amount of M5 used per 4- × 4-in. aluminum plate.

Figure 4

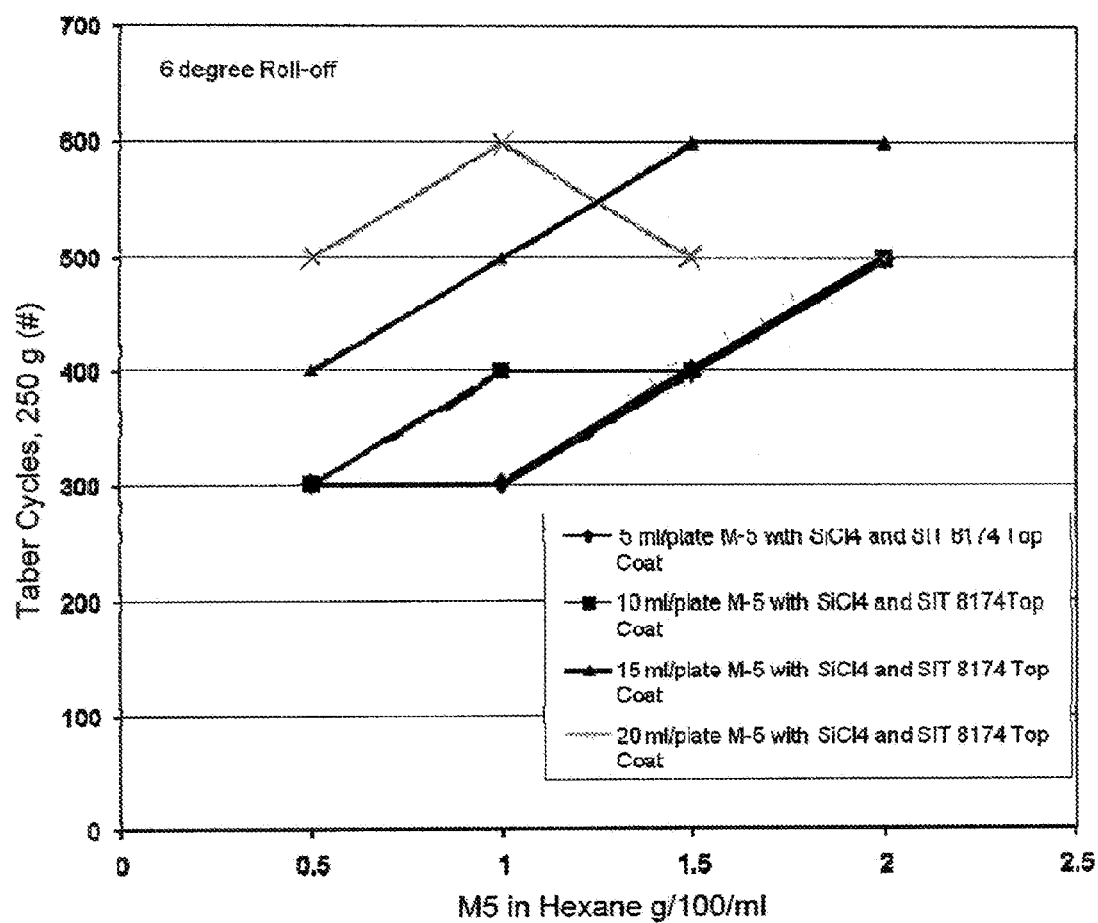


Figure 5

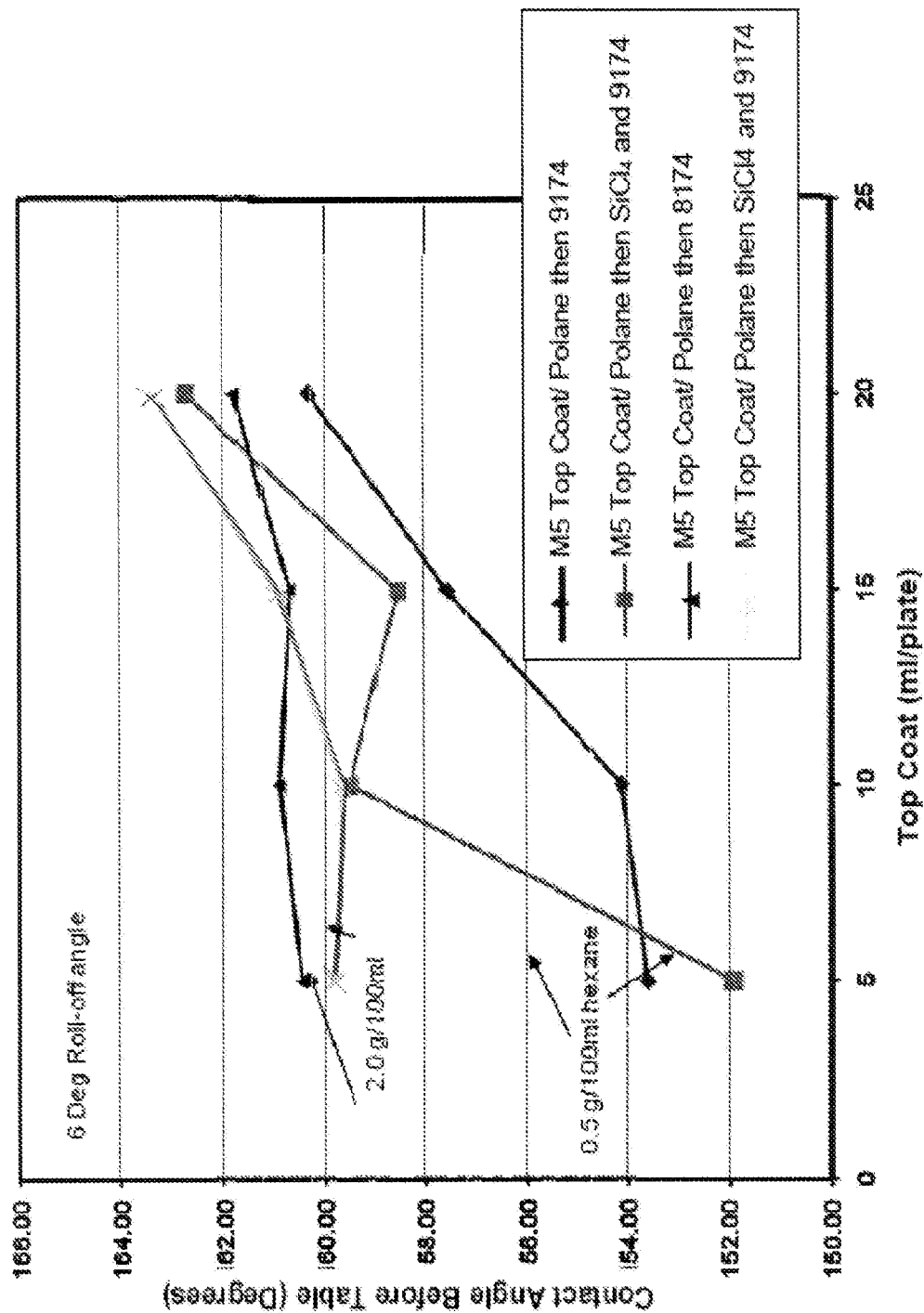


Figure 6

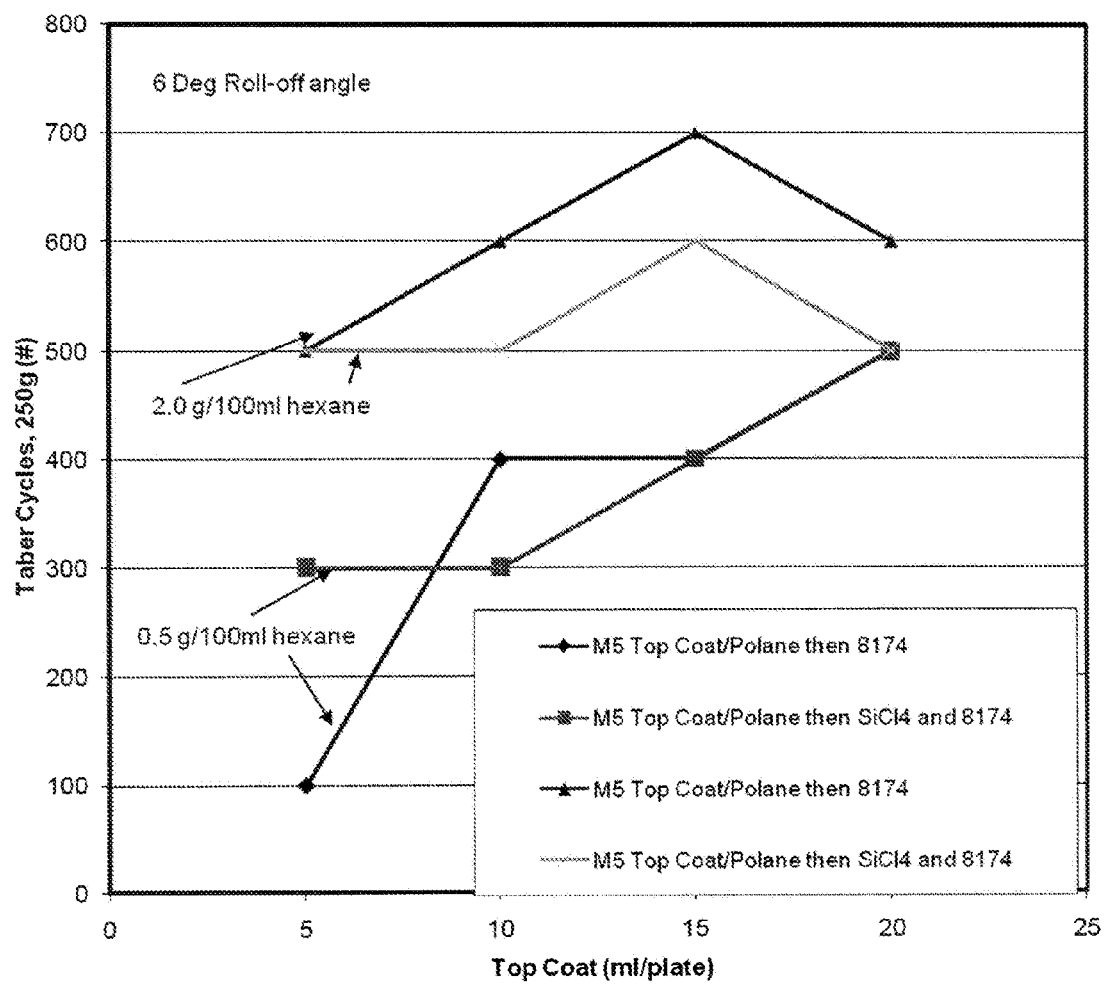


Figure 7

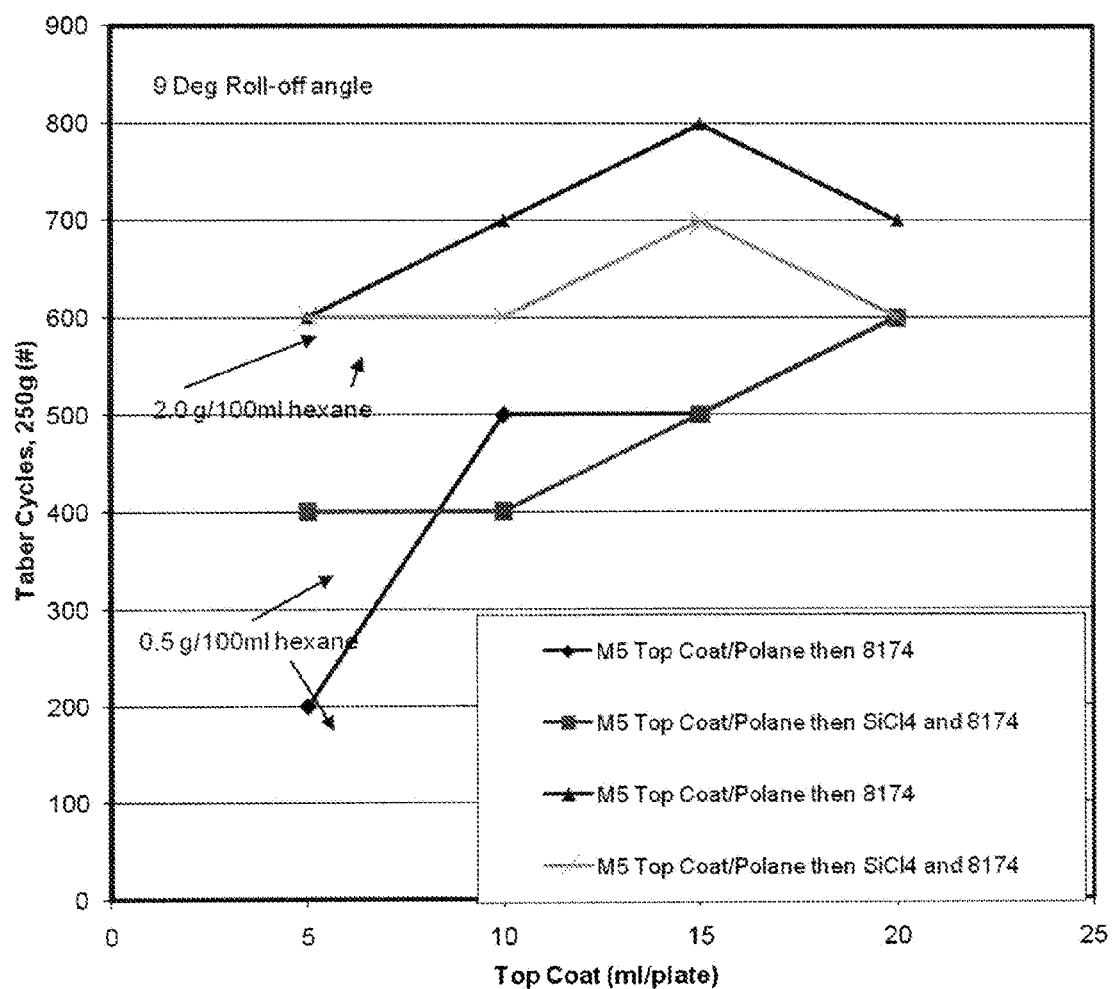




Figure 8

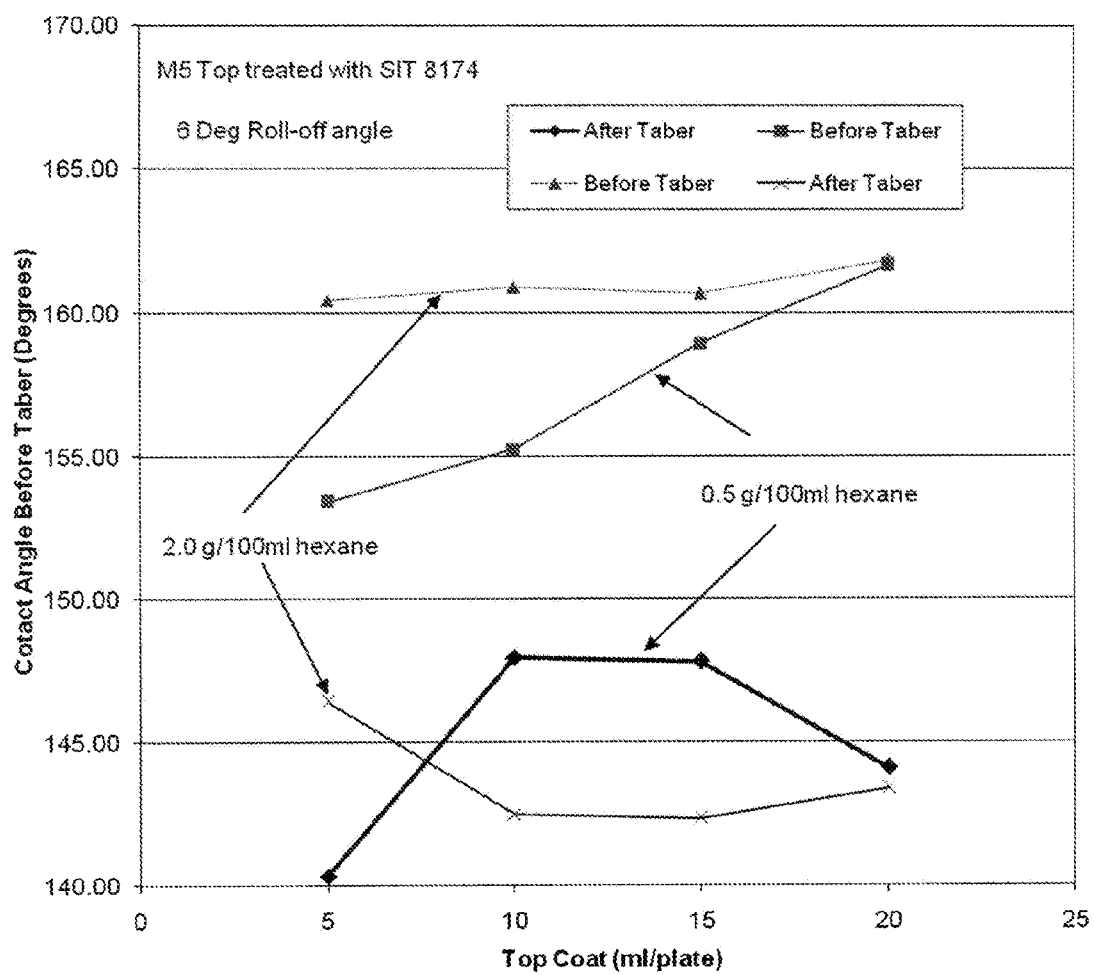


Figure 9

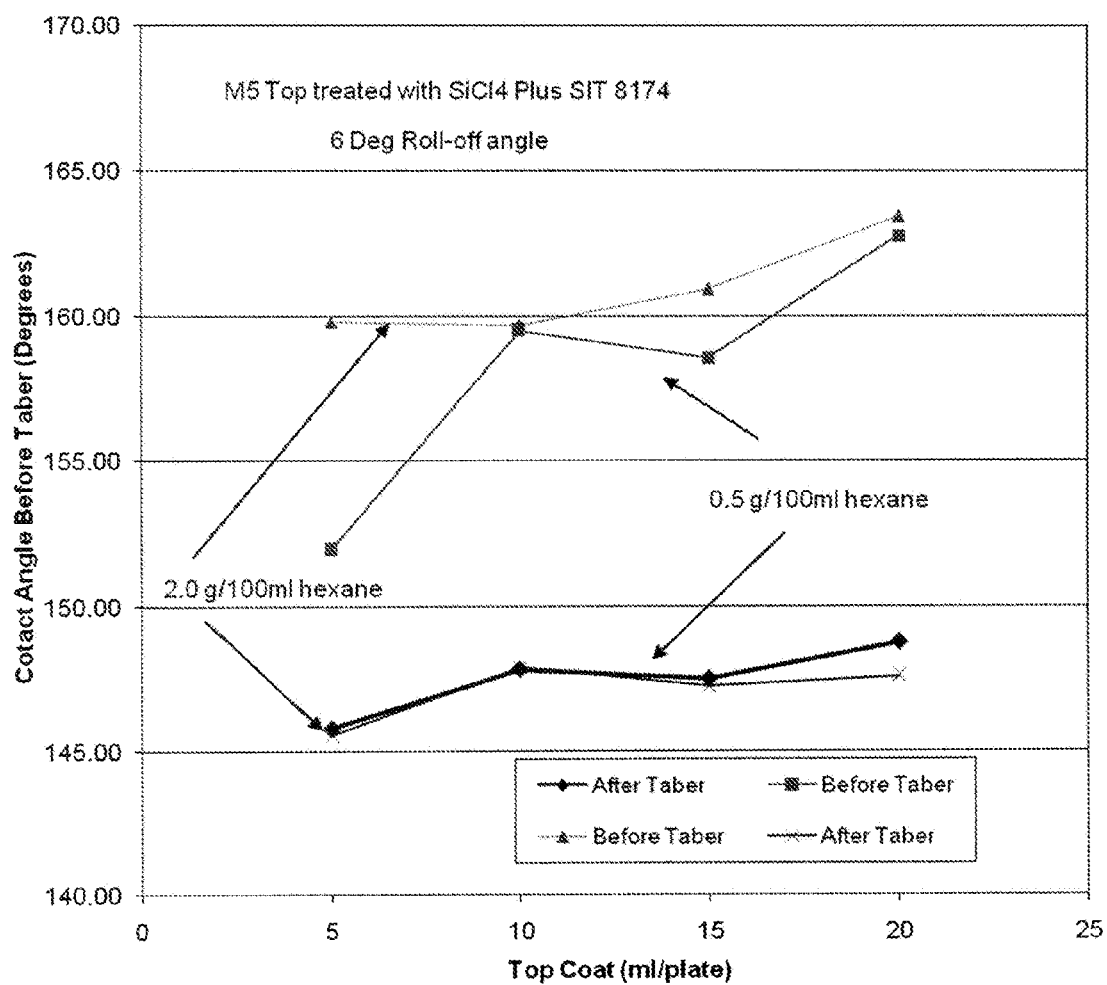


Figure 10

Panel (a)

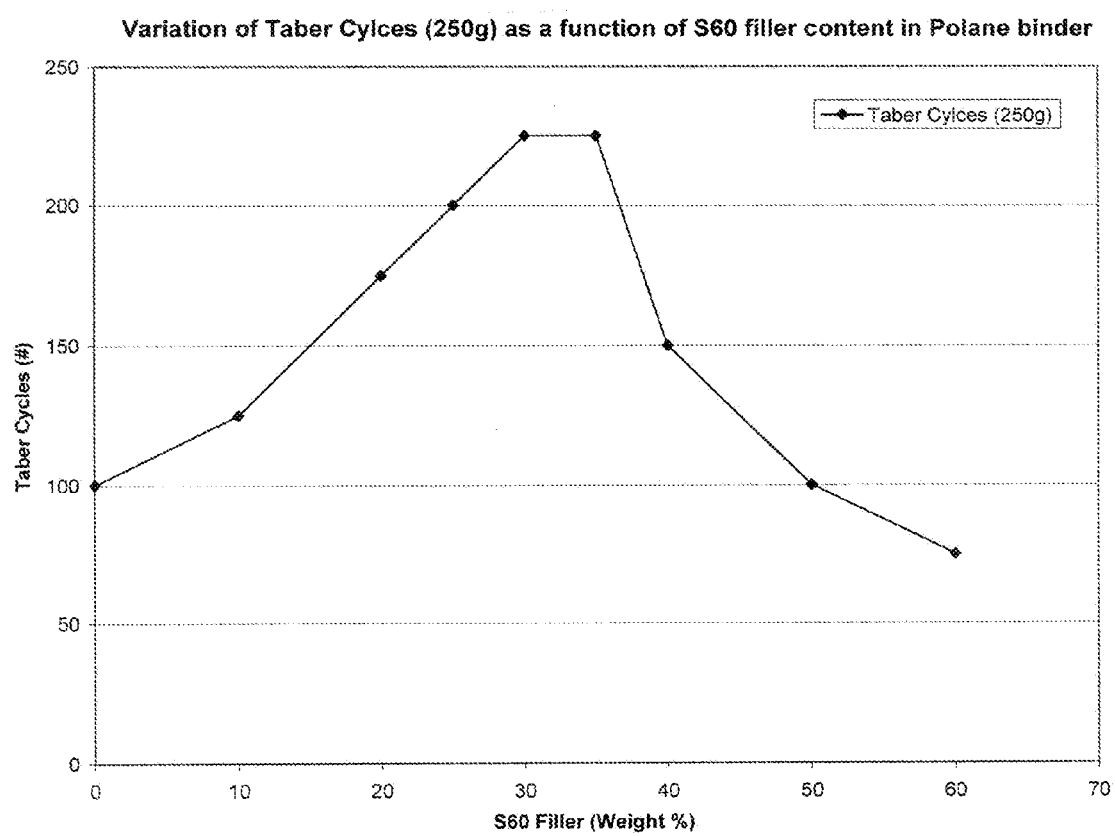


Figure 10

Panel (b)

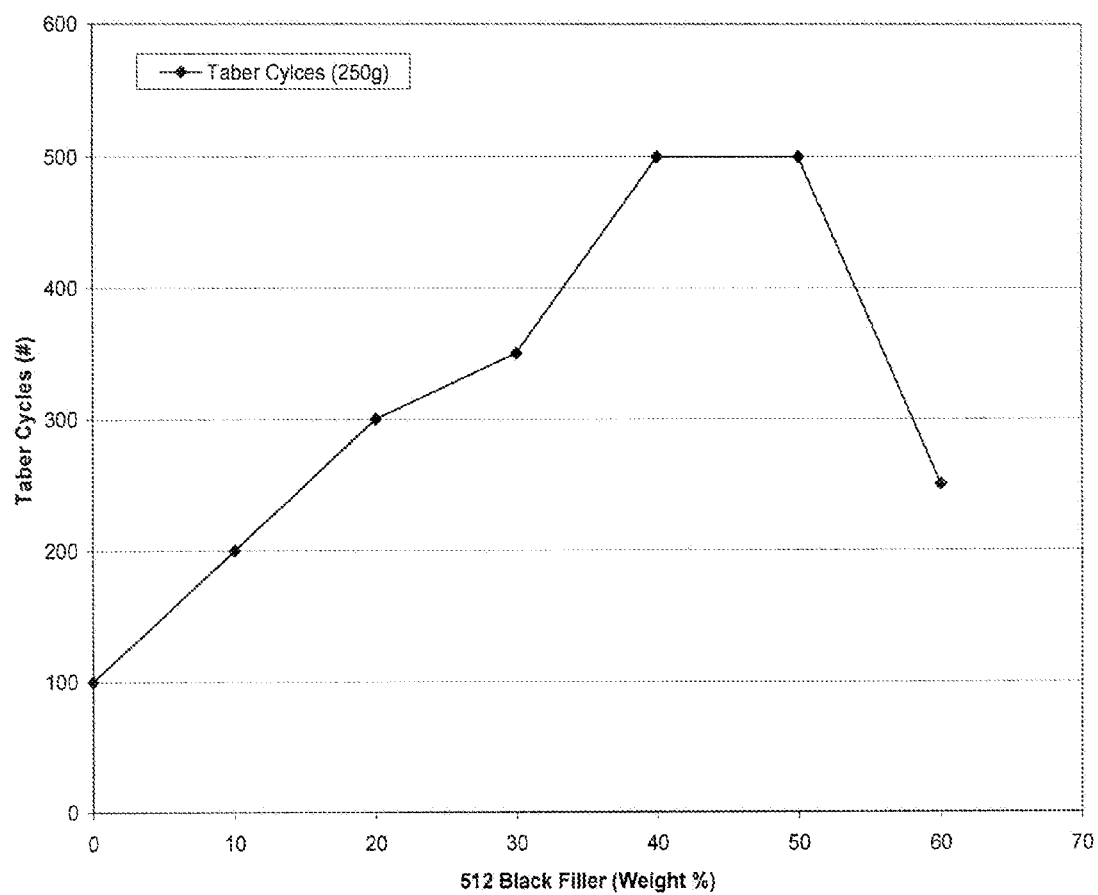


Figure 11

Panel (a)

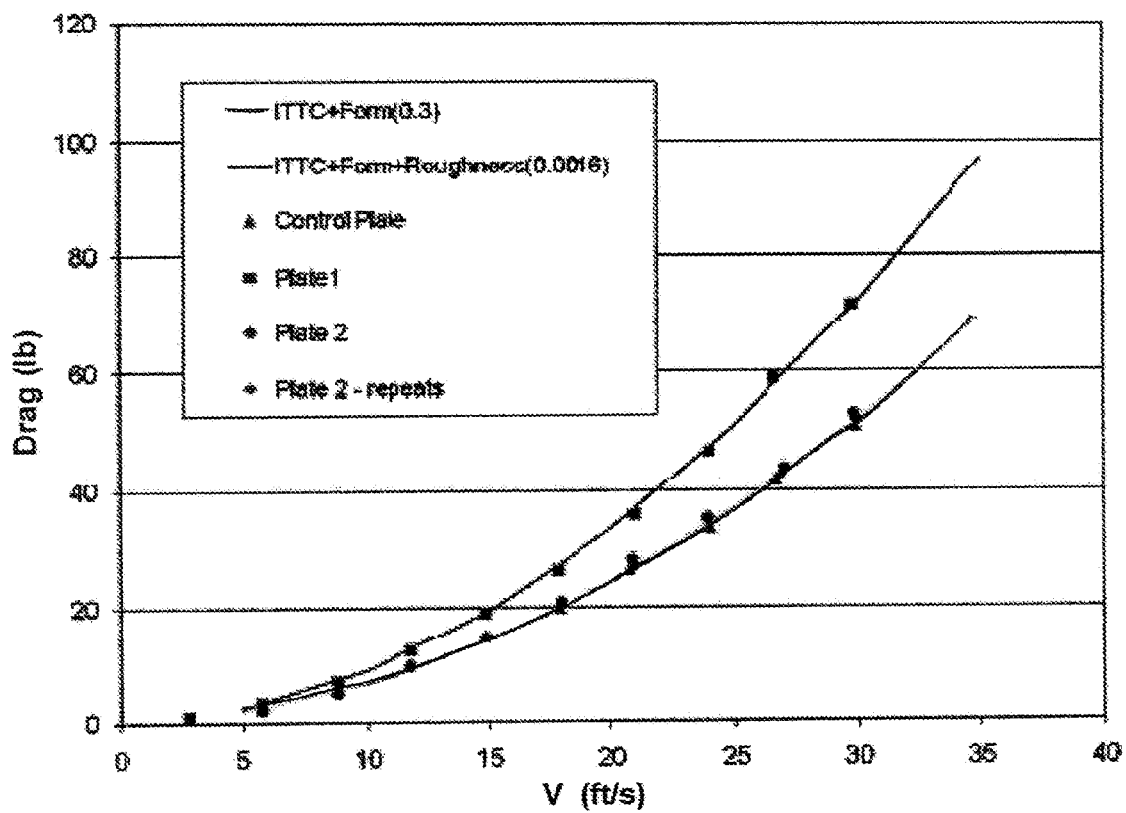


Figure 11

Panel (b)

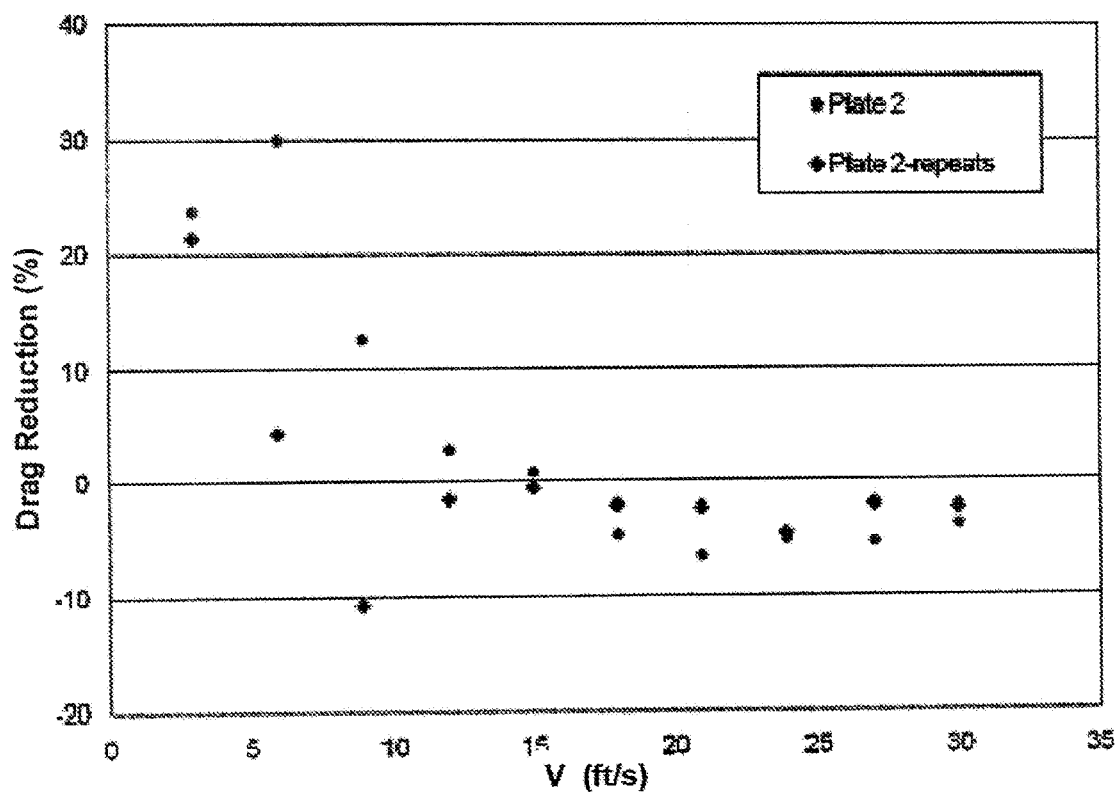


Figure 12

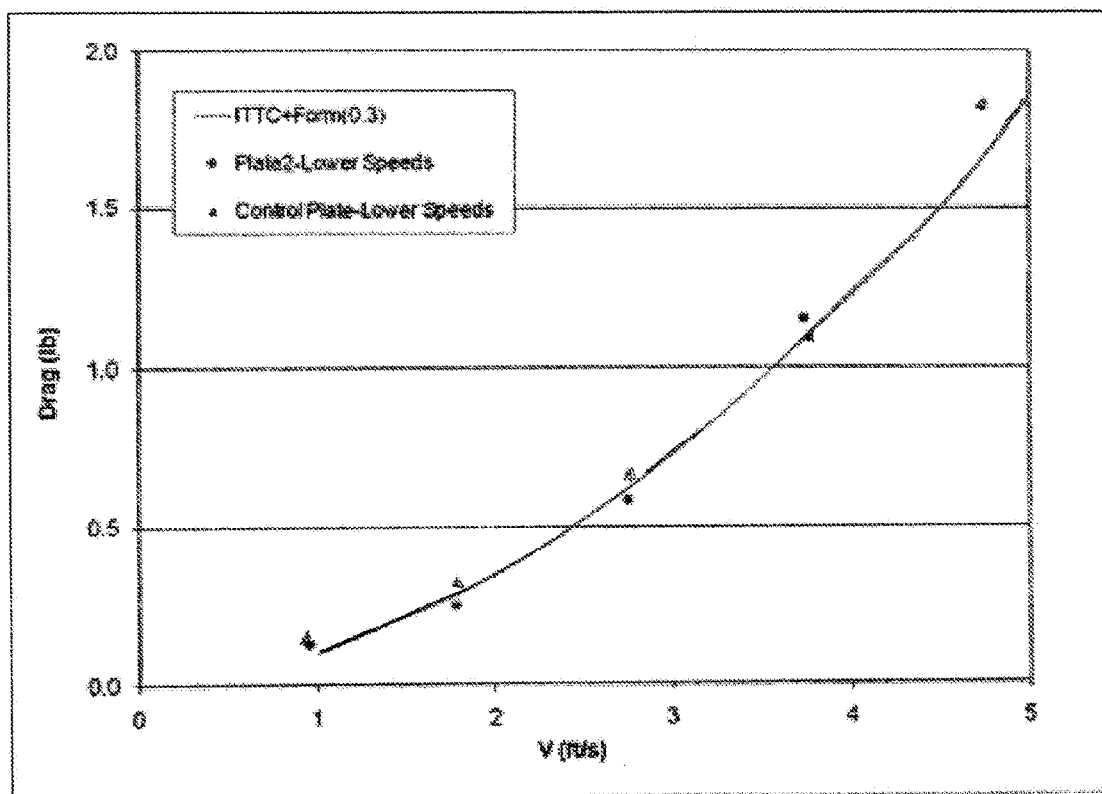


Figure 12

Panel (b)

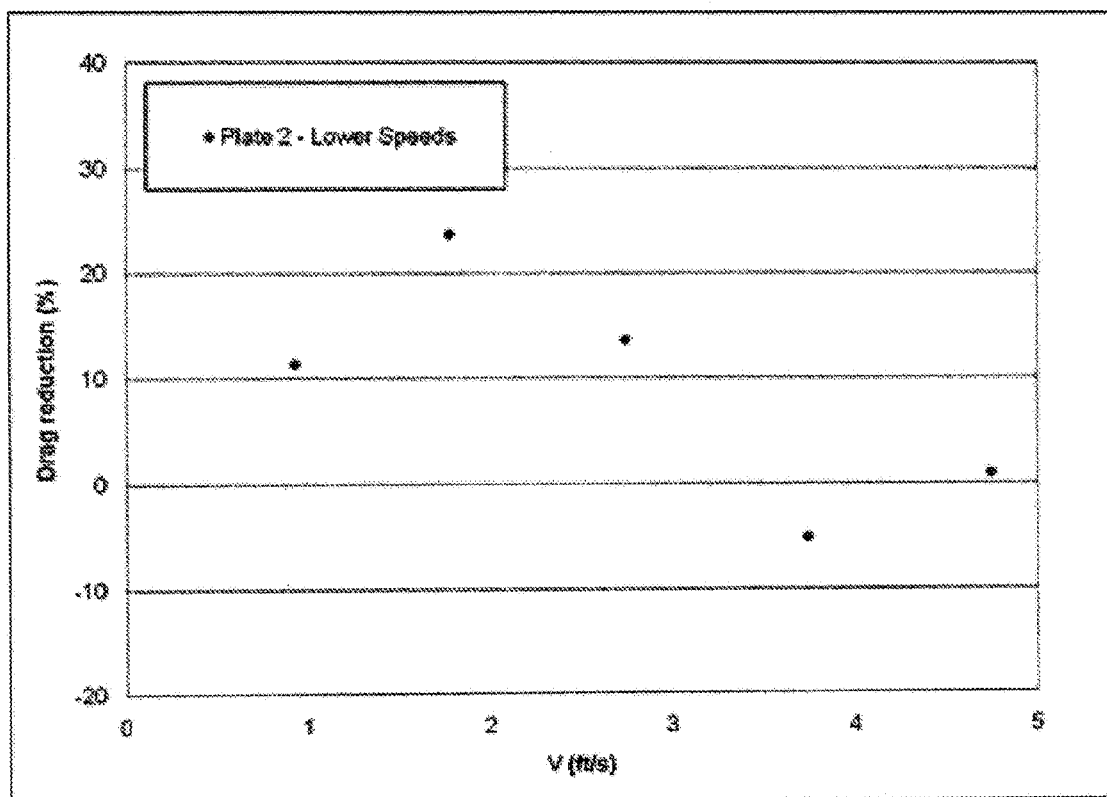




Figure 13

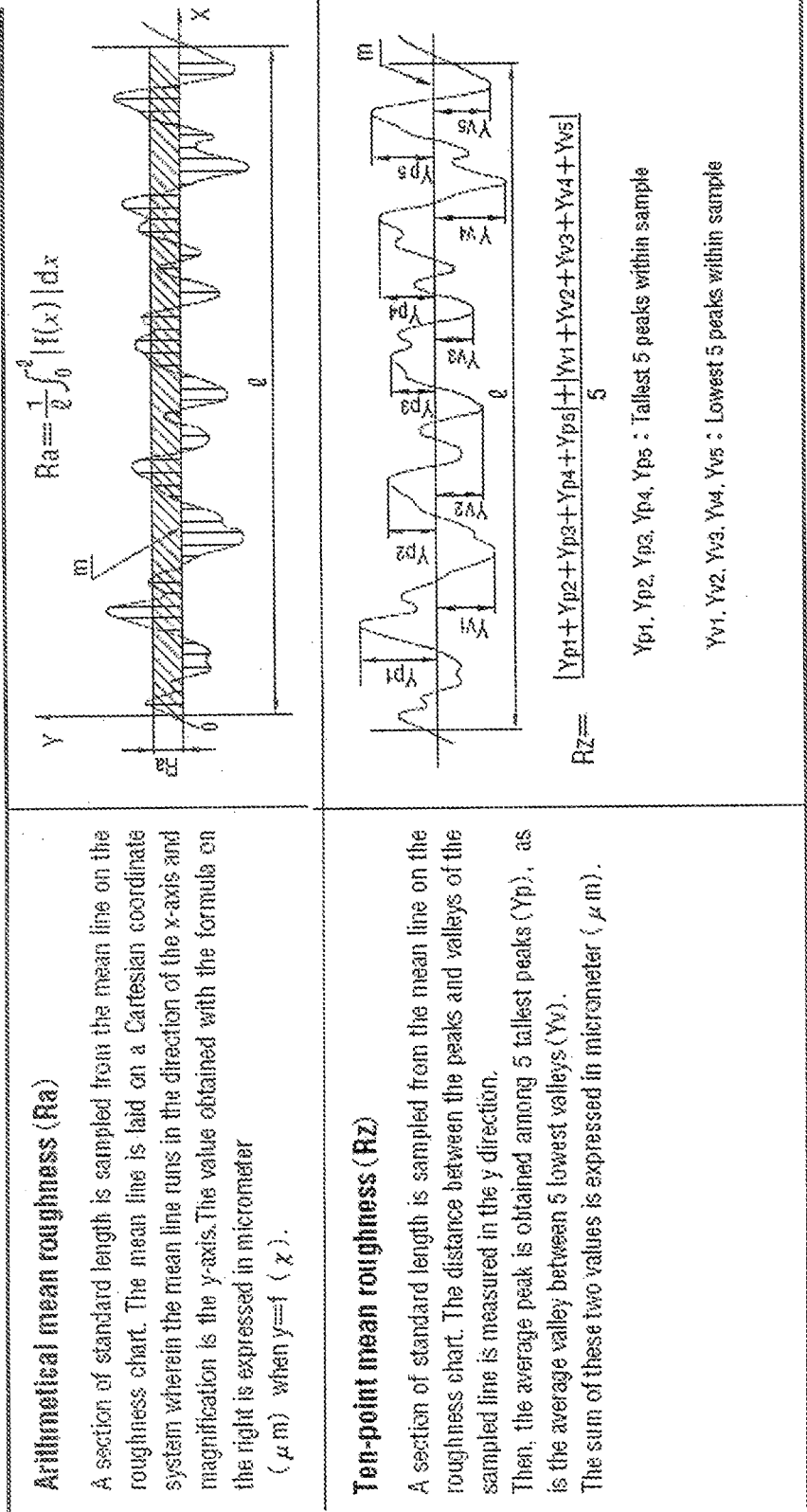
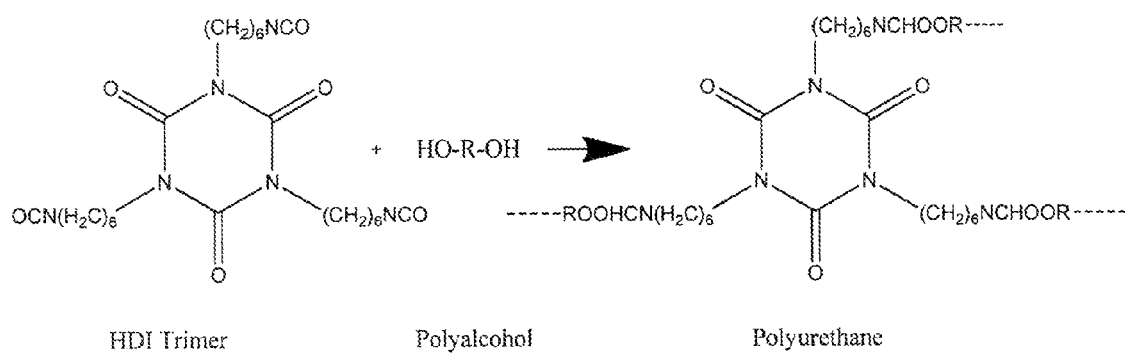


Figure 14



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# HIGHLY DURABLE SUPERHYDROPHOBIC, OLEOPHOBIC AND ANTI-ICING COATINGS AND METHODS AND COMPOSITIONS FOR THEIR PREPARATION

This application is a continuation of PCT/US2009/005512, filed Oct. 7, 2009, which claims the benefit of priority to U.S. Provisional Application No. 61/103,295, filed on Oct. 7, 2008, and U.S. Provisional Application No. 61/159,914, filed Mar. 13, 2009, the contents of each of which are hereby incorporated by reference in their entireties.

## BACKGROUND

Consumer and industrial products are made from a variety of materials including: metals and alloys, wood, glass, ceramics, cement and other masonry products, fabrics, plastics, paper, and composites. Composites of such materials can be composed of, for example, metals, masonry, or polymer based products. In all cases, surfaces of the products that are exposed to the environment may come into contact with a variety of agents, including dust, moisture, water, and oils. In industrial applications, surfaces may be exposed to a variety of agents such as water, aqueous salt solutions, solutions of aqueous acid or base, and chemicals that may be dissolved or suspended in aqueous compositions or other liquids that are used in manufacturing processes. Not only are product surfaces exposed to a variety of agents, but the temperatures to which surfaces are exposed can also affect their performance. For example, freezing liquids, such as water, can result in frozen deposits tightly attached to the surfaces exposed to the liquids, preventing access to the surface and preventing proper operation of equipment bound by the frozen liquids. In addition, elevated temperatures can accelerate processes such as corrosion or preferential surface leaching effects.

## SUMMARY

Highly durable coatings and surface treatments are provided having a variety of surface properties including, but not limited to: hydrophobicity/superhydrophobicity, oleophobicity, resistance to ice formation and/or ice deposition (adherence). Compositions that are hydrophobic and/or oleophobic and/or anti-icing ("HP/OP") may be applied to a surface using single-step or multiple steps (e.g., two-step coating processes). Methods of applying such coatings and surface treatments also are provided, together with compositions for applying such coatings and surface treatments, and objects comprising coated and treated surfaces.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows two types of coatings on glass plates. Shown in FIG. 1 (perspective vertically down) are three glass plates. Panel A depicts the plates in the absence of liquid and Panel B depicts the plates in the presence of liquid. Plate "(A)" is a "control" glass plate without any spill-resistant border; plate "(B)" is a glass plate bearing a spill-resistant HP/OP border prepared by applying a coating to the border region; and plate "(C)" is a glass plate bearing a spill-resistant HP/OP border prepared by applying a tape bearing a HP/OP coating to the border region.

FIG. 2 depicts five different surfaces with regions (stippled) that have a lower hydrophobicity and/or lower oleophobicity than the spill-resistant border and spill-resistant borders as unmarked (white) regions. In (A), a surface with a spill resistant border in the form of an edge (at its edge) is

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depicted. (B) shows a surface with a spill resistant border in the form of a spill-resistant edge along with two diagonal spill resistant barriers. The diagonal barriers may retain liquids at the same height as the spill-resistant edge or optionally may have a lesser ability to retain liquids than the border at the edge (i.e., the barrier lines optionally may retain liquids to lower heights than the border at the edge). (C) shows a surface with a spill resistant border in the form of a spill-resistant edge along with a series of spill resistant barriers in the form of a grid, where the barrier lines optionally may have a lesser ability to retain liquids than the edge. (D) depicts a surface with a spill resistant border in the form of a spill-resistant edge along with a series of partial spill resistant barriers, that optionally may have a lesser ability to retain liquids and which may be used to channel liquids toward a drain (or drains), or a site where one or more drain tube(s) are connected (black oval). The barrier lines in such an embodiment may extend to the drain. (E) shows a surface with a spill resistant border in the form of a spill-resistant edge along with two diagonal spill resistant barriers that terminate at a drain (black oval). The diagonal barriers lines optionally may have a lesser ability to retain liquids than the edge and can be used to channel or direct liquids to the drain. Where drains are attached to a surface, the surface may be inclined or depressed so that the opening of the drain is lower than the edge of the surface, channeling liquids to the drain.

FIG. 3 shows resistance to abrasion measured by the number of abrasion cycles in a Taber test for different concentrations and amounts of M5 silica treated with the silanizing agent SIT8174 applied to a base coat on aluminum plates.

FIG. 4 shows resistance to abrasion measured by the number of abrasion cycles in a Taber test for different concentrations and amounts of M5 silica treated with the  $\text{SiCl}_4$  followed the silanizing agent SIT8174 applied to a base coat on aluminum plates.

FIG. 5 graphs contact data for water measured at 18°-22° C. on plates treated with a HP/OP coating before Taber testing plotted as a function of the amount of treated silica (M5 fumed silica treated with either the silanizing agent SIT8174 or  $\text{SiCl}_4$  followed the silanizing agent SIT8174) applied to a base coating during plate preparation.

FIGS. 6 and 7 show plots of the abrasion resistance as measured by Tabor abrasion cycles plotted as a function of the amount of treated silica (M5 fumed silica treated with either the silanizing agent SIT8174 or  $\text{SiCl}_4$  followed the silanizing agent SIT8174) for the plates described in FIG. 3. The end of hydrophobicity is assessed by the propensity of water droplets to remain on plates inclined at a 6° (FIG. 4), or a 9° (FIG. 5) from level.

FIGS. 8 and 9 show plots of the water contact angle measured at 18°-22° C. after abrasion testing, plotted as a function of the amount of treated silica applied to the plates described in FIG. 3. The end of hydrophobicity is assessed the propensity of water droplets to remain on plates inclined at 6° (FIG. 4), or 9° (FIG. 5) from level.

FIG. 10 (Panels 10a and 10b) are plots of the variation in abrasion resistance (measured by Taber cycle) as a function of first particle content on a percent weight basis; S60 second particles in Panel 10a (see Table 10b), or 512 Black second particles in Panel 10b (see table 10d).

FIG. 11 panels (a) and (b) show the results of testing plates A and B at various water flow speeds covering both laminar and turbulent flows. Three plates are tested: a control, which has a smooth reference surface with no coating; Plate A (indicated as plate 1 in the figure); and Plate B (indicated as plate 2 in the figure) describe in Example 19.

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FIG. 12: Panel (a) is a plot of total drag measured at varying water speeds and Panel (b) is a plot of drag reduction produced by HP/OP coatings for the plates described in Example 19, compared to an uncoated aluminum plate that is otherwise identical to the coated plates.

FIG. 13 shows the arithmetic mean roughness and 10 point mean roughness.

FIG. 14 shows a polyisocyanate trimer.

#### DETAILED DESCRIPTION

Coating methods and compositions/treatments are provided that impart a variety of desirable characteristics to objects and their surfaces, including hydrophobicity (e.g., superhydrophobicity), oleophobicity and anti-icing. Those characteristics can result in objects and surfaces with a variety of desirable properties including, but not limited to, resistance to: wetting, corrosion, swelling, rotting, cracking or warping, exfoliation, fouling, dust and/or dirt accumulation on surfaces (self cleaning), and surface ice formation adherence and accumulation. The coating compositions and treatments not only provide hydrophobicity and/or oleophobicity and/or anti-icing properties, but are durable in that they resist mechanical abrasion while retaining those properties

The coatings may be applied using a variety of techniques that can be grouped into three categories: one-step processes; two-step processes; and thermal deposition processes, which may in some instances be considered a special case of one-step or two-step processes. Within each of those categories numerous variations and embodiments are provided.

In some embodiments, the coatings may be applied using a one-step method, where a binder, first particles, and second particles are mixed to provide a coating composition that is then applied to the surface.

For example, a one-step method of applying a coating to a substrate may apply a coating composition to a substrate where the components include: i) a binder; ii) first particles having a size of about 30 microns to about 225 microns; and iii) second particles having a size of about 1 nanometer to 25 microns. Optionally, one or more independently selected alkyl, haloalkyl, or perfluoroalkyl groups may be covalently bound, either directly or indirectly, to the second particles. The composition optionally may contain 5% to 10% of a block copolymer on a weight basis. The composition may also contain any necessary solvents/liquids to assist in the application process.

Particles suitable for use in these compositions are described in detail below.

Where second particles are not HP/OP (e.g., untreated with a silanizing agent) prior to their incorporation into a coatings formed in one or two step processes, the coatings formed in those processes may be treated to apply chemical moieties (groups) such as alkyl, haloalkyl, fluoroalkyl or perfluoroalkyl groups to the second particles at the surface of the coating (e.g., treating with silanizing agents such as compounds of formula (I), SIT7184.0 and the like).

In some embodiments, the coatings may be applied using two-step methods, where, in a first step, a binder and first particles are mixed to form a coating composition, which does not contain the second particles prior to the application of the coating composition to the surface. Once applied, the coating composition is termed a "substrate coating" or a "base coat." Following the application of that coating composition, a composition comprising second particles is applied in a second step to the surface over the coating composition.

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In some embodiments a two-step method of applying a coating to a substrate comprises:

- a) applying to the substrate a coating composition comprising i) a binder and ii) first particles having a size of about 30 microns to about 225 microns, to provide a base coating; and
- b) applying to this base coating a composition containing second particles having a size of about 1 nanometer to 25 microns. The second particles may have one or more independently selected alkyl, haloalkyl or perfluoroalkyl groups (e.g., polydimethylsiloxane) covalently bound, either directly or indirectly, to the second particles.

The composition may also contain any necessary solvents/liquids to assist in the application process.

In some embodiments of a two-step application method, the base coating is treated with the composition containing second particles after drying and curing the base coating at room temperatures (about 18-22° C.) or elevated temperatures (e.g., about 93° C.). In other embodiments, solvent used to apply the base coat is allowed to evaporate until the coating is no longer liquid and cannot be removed by contact; however, the base coating is not cured, when treated with the composition containing second particles. In still other embodiments, the composition comprising second particles may be applied directly to the base coat before solvents used in the application of the base coating have evaporated fully, substantially or even partly.

In one embodiment where HP/OP coatings are prepared using thermal spray processes, the process is a two step process. In such processes the metals and other materials applied to a substrate by thermal spray processes may be considered as binders for first particles added to the composition sprayed in the first step (e.g.,  $\text{Al}_2\text{O}_3$ , silica or other metalloid oxides, or metal oxides). Alternatively the materials applied to the substrate may be considered as a binder for materials formed in the spraying process (e.g., metal or metalloid oxides formed in the spray process with oxidizing fuel). In addition to applying first particles, thermal spraying processes can also apply second particles and materials formed in the spraying process (e.g., metal oxides or metalloid oxides from the spraying composition). In each of those instances, following thermal spray treatment, the surface will contain materials (e.g., metal oxides) that can bind the materials or react with reagents that will enhance or impart HP/OP properties to the substrate's surface. Alternatively, the materials applied as a base coating, which form a rough surface, may be considered to comprise first particles formed from the materials applied in the partly melted and fused coating composition. In either case, following thermal spray deposition the surface is subject to a second treatment to enhance or impart HP/OP properties to the surface.

In one embodiment a method for thermal deposition of a coating to a surface may include the steps of:

- a) applying to the substrate by a thermal spray process a base coating spray composition optionally comprising one or more independently selected first particles having a size of about 1 micron to about 100 microns, to provide a base coating; and
- b) applying to this base coating one or more of: i) a composition comprising one or more independently selected second particles having a size of about 1 nanometer to 25 microns that optionally comprise one or more independently selected alkyl, haloalkyl, fluoroalkyl, or perfluoroalkyl groups covalently bound, either directly or indirectly, to the second particles; ii) a composition comprising one or more independently selected silaniz-

ing agents or iii) a composition comprising a silicon-containing reagent that will increase the number of Si—OH sites, followed by a composition containing a silanizing agent.

Diverse binders, first particles, second particles and block copolymers may be employed in the methods and compositions described herein. In some embodiments, first particles may be considered filler particles. Similarly, in some embodiments second particles may be considered nanoparticles. In each instance, those materials are described more fully below.

A skilled artisan will understand that the selection of first particles and second particles needs to consider not only the desired properties of the coating and the ultimate conditions to which the coating will be subject in use, but also the process used to prepare the coating. Where, for example, particles must withstand elevated temperatures or specific solvents in the coating process, they need to be suitable for use in the required temperature ranges or in the required solvents. For example, in those embodiments where first and/or second particles are used with a thermoplastic binder, the particles need to be compatible with the elevated temperatures that are required to cure thermoplastic binders. In other embodiments where, for example, first particles or second particles are applied as part of a thermal spray composition, the particles need to withstand the high temperatures associated with those processes.

The one-step and two-step methods described herein can in some embodiments be used to produce coatings where the coating has (i) a surface in contact with said substrate and (ii) an exposed surface that is not in contact with the substrate where these surfaces bear different amounts of first particles, second particles, or both first and second particles. In such embodiments the exposed surface can have a greater amount of second and/or first particles on, at, or adjacent to the exposed surface, compared to the amount of first and/or second particles at or adjacent to the surface of the coating that is in contact with the substrate.

In other embodiments, the one-step and two-step methods described herein can be used to produce coatings where the coating has (i) a surface in contact with said substrate, (ii) an exposed surface that is not in contact with the substrate and a (iii) central portion of the coating that is between these surfaces. In such embodiments the exposed surface can have a greater amount of second and/or first particles on, at, or adjacent to the exposed surface, compared to the amount of first and/or second particles in the central region of the coating.

In embodiments where a greater amount of first and/or second particles may be present at the exposed surface, the coatings may be considered composite coatings. Such composite coatings may be formed using either one- or two-step application processes.

In one-step coating processes the incorporation of a block copolymer in a range selected from: about 35 to about 15%; from about 4% to about 13%; from about 5% to about 10% or 4% to about 7% (by weight of the final cured coating) can result in the movement of first or second particles to the surface of the coating. Without wishing to be bound by any theory, it is believed that block copolymers may form aggregates in the binder composition, which can cause localization of at least second particles, and may also cause localization of first particles as well.

In two step processes, composite coatings with a greater amount of first and/or second particles may be present at the surface as a result of their being applied to the exposed surface of the base coating. Furthermore, where the base coating composition comprises a block copolymer in the ranges listed above for one step applications, first and/or second particles

present in the base coating may move to the surface, which will also create an unequal distribution of particles in the coating.

The amount of particles in any portion of a coating may be assessed by any means known in the art including, but not limited to, microscopy or electron microscopy. Using those techniques and cross or oblique sections of coatings, the amount (e.g., the number) of particles can be determined. In addition, where it is possible to remove coatings, or where the substrate permits (e.g., it is transparent), the surfaces can be examined directly using microscopy or electron microscopy to determine the amount of particles present at the surface adjacent to the coating.

The coatings described herein are durable and resistant to the loss of OH/OP properties as a result of abrasion. Resistance to abrasion may be measured using any method known in the art including assessment with a Taber abrasion testing instrument (e.g., a Taber “Abraser”). For the purpose of this application, wherever Taber testing results are recited, the tests were conducted on a Taber Model: 503 instrument using CS-10 wheels with 250 g or 500 g loads as indicated. Abrasion may also be measured using manual tests as described in Example 1. To provide an end point for the loss of hydrophobicity (and also oleophobicity and anti-icing properties) as a result of abrasion testing, surfaces are tested for their propensity to shed water droplets at an indicated angle of incline. Typically, twenty droplets are placed on the surface to be assessed, which is then inclined at the desired angle. End of life is indicated when more than half (ten or more drops) stay in place. While such measurements provide a consistent end point, a skilled artisan will understand that even after abrasion testing the abraded surfaces may still be quite hydrophobic, having water contact angles greater than 130 or 140° in many instances.

In addition to resistance to loss of OH/HP properties from abrasion, the compositions provided herein also provide durability in the form of resistance to other conditions. The coatings, which employ diverse binder systems, also display durability in:

- Submerged water durability testing (the duration of a coating to resist wetting at different depths in water);
- Mechanical durability testing under high pressure impingement of water (the resistance of coating or surface treatment to the impact of high-pressure water);
- Chemical durability testing (the resistance of the coatings and treatments to liquids other than water, such as acids, alkalis, salts, and organic solvents such as alcohols, acetone, toluene, xylene, etc.);
- UV radiation resistance testing;
- Tests for resistance to boiling water; and
- Ice formation and/or adherence testing.

In addition to their other properties, the HP/OP coating described herein can be described by their characteristic roughness that may be measured by any means known in the art. In some embodiments the surface roughness is measured using a Mahr PocketSurf PS1 (Mahr Federal Inc., Providence, R.I.). The roughness can be expressed using a variety of mathematical expressions including, but not limited to, the Arithmetical Mean Roughness and Ten-Point Mean Roughness, which are described FIG. 13.

The coatings, resulting from the application of the compositions provided for herein, have in some embodiments a surface with an arithmetical mean roughness in a range selected from: greater than about 3 microns to about 4 microns; from about 4 microns to about 6 microns; from about 4 microns to about 8 microns; from about 4 microns to about 12 microns; from about 4 microns to about 20 microns;

from about 5 microns to about 10 microns; from about 5 microns to about 12 microns; from about 5 microns to about 20 microns; from about 6 microns to about 10 microns; or from about 6 microns to about 14 microns.

In other embodiments, the coatings, resulting from the application of the compositions provided for herein, have in some embodiments a surface with a ten point mean roughness selected from: greater than about 7 microns to about 60 microns; from about 7 microns to about 70 microns; from about 7 microns to about 80 microns; from about 7 microns to about 100 microns; from about 8 microns to about 60 microns; from about 8 microns to about 80 microns; from about 8 microns to about 100 microns; from about 12 microns to about 60 microns; from about 12 microns to about 100 microns; from about 15 microns to about 60 microns; or from about 15 microns to about 100 microns.

In some embodiments the coating surface has projections due to the presence of the first particles, with a maximum height above the level of the binder in a range selected from: from about 10 to about 180 microns; from about 15 to about 150 micron; from about 20 to about 100 microns; from 30 to 120 microns; from about 40 to 140 microns; from about 50 to about 150 microns, or from about 20 to about 80 microns.

A more complete discussion of the compositions and methods of their application and surface treatments follow. A skilled artisan will understand that the following description and examples are provided as guidance, and are not limiting to the scope of the methods and compositions described herein.

## 1.0 DEFINITIONS

For the purposes of this disclosure a hydrophobic border or surface is one that results in a water droplet forming a surface contact angle exceeding about 90° and less than about 150° at room temperature (about 18 to about 23° C.). Similarly, for the purposes of this disclosure a superhydrophobic border or surface is one that results in a water droplet forming a surface contact angle exceeding about 150° but less than the theoretical maximum contact angle of about 180° at room temperature. Some authors further categorize hydrophobic behavior and employ the term “ultrahydrophobic.” Since for the purposes of this disclosure, a superhydrophobic surface has contact angles of about 150° to about 180°, superhydrophobic behavior is considered to include ultrahydrophobic behavior. For the purpose of this disclosure the term hydrophobic shall include superhydrophobic unless stated otherwise.

For the purposes of this disclosure an oleophobic material or surface is one that results in a droplet of light mineral oil forming a surface contact angle exceeding about 25° and less than the theoretical maximum contact angle of about 180° at room temperature.

Anti-icing (AI) surfaces are surfaces that are resistant to ice formation or prevent ice that forms from adhering to the surface (i.e., ice that forms can be removed with a minimum of force).

For the purpose of this disclosure HP/OP denotes hydrophobic (including superhydrophobic) and/or oleophobic behavior or properties as well as anti-icing properties. Durability, unless stated otherwise, refers to the resistance to loss of hydrophobic properties due to mechanical abrasion.

Alkyl as used herein denotes a linear or branched alkyl radical. Alkyl groups may be independently selected from C<sub>1</sub> to C<sub>20</sub> alkyl, C<sub>2</sub> to C<sub>20</sub> alkyl, C<sub>4</sub> to C<sub>20</sub> alkyl, C<sub>6</sub> to C<sub>18</sub> alkyl, C<sub>6</sub> to C<sub>16</sub> alkyl, or C<sub>6</sub> to C<sub>20</sub> alkyl. Unless otherwise indicated, alkyl does not include cycloalkyl. Cycloalkyl groups may be independently selected from: C<sub>4</sub> to C<sub>20</sub> alkyl comprising one

or two C<sub>4</sub> to C<sub>8</sub> cycloalkyl functionalities; C<sub>4</sub> to C<sub>20</sub> alkyl comprising one or two C<sub>4</sub> to C<sub>8</sub> cycloalkyl functionalities; C<sub>6</sub> to C<sub>20</sub> alkyl comprising one or two C<sub>4</sub> to C<sub>8</sub> cycloalkyl functionalities; C<sub>6</sub> to C<sub>18</sub> alkyl comprising one or two C<sub>4</sub> to C<sub>8</sub> cycloalkyl functionalities; C<sub>6</sub> to C<sub>16</sub> alkyl comprising one or two C<sub>4</sub> to C<sub>8</sub> cycloalkyl functionalities. One or more hydrogen atoms of the alkyl groups may be replaced by fluorine atoms.

Haloalkyl as used herein denotes an alkyl group in which some or all of the hydrogen atoms present in an alkyl group have been replaced by halogen atoms. Halogen atoms may be limited to chlorine or fluorine atoms in haloalkyl groups.

Fluoroalkyl as used herein denotes an alkyl group in which some or all of the hydrogen atoms present in an alkyl group have been replaced by fluorine atoms.

Perfluoroalkyl as used herein denotes an alkyl group in which fluorine atoms have been substituted for each hydrogen atom present in the alkyl group.

For the purpose of this disclosure, when content is indicated as being present on a “weight basis” the content is measured as the percentage of the weight of components indicated, relative to the total weight of the binder system. When a liquid component such as a commercial binder product is used, the weight of the liquid component is used to calculate the weight basis, without regard to the relative amounts of solute and solvent that might be present in the commercial product. Thus, for example, when Polane is used as a binder, the weight basis is calculated using the weight of the Polane prepared as instructed by the manufacturer, without regard to the proportions of polyurethane solute and organic solvents. Optional solvents that are separately added to a composition merely to, for example, dilute the composition to a thickness suitable for spraying, are not included in the calculation of content on a weight basis.

## 2.0 BINDERS

Binders used to prepare durable superhydrophobic coatings may have a variety of compositions. Virtually any binder may be employed that is capable of adhering to the surface to be coated and retaining the desired first and second particles, both of which are described below. In some embodiments the binders employed are hydrophobic or superhydrophobic as applied in the absence of any added first or second particles, which can be advantageous in the preparation of durable HP/OP coatings.

In some embodiments the binders may be selected from lacquers, polyurethanes, fluoropolymers, epoxies, or powder coatings (thermoplastics). In other embodiments the binders may be selected from lacquers, polyurethanes, fluoropolymers, or thermoplastics. Binders may be hydrophilic, hydrophobic or superhydrophobic “as applied.” For the purposes of this disclosure, when binders or their properties are described “as applied,” it is understood that the binder(s) and properties are being described in the absence of the first and second particles described herein that alter the durability, hydrophobic/superhydrophobic and oleophobic properties of binder.

In one- or two-step processes, where the binders employed are hydrophilic, the coating will generally be given an application of a silanizing agent after it has been applied to the substrate.

In some instances, the binders are not comprised of materials (e.g., monomers or oligomers) that polymerize when exposed to UV light to form polymers. In another embodiment, the binders are not comprised of thermoset polymeric materials.

Regardless of what type of binder is employed, one consideration in choosing a suitable binder is the compatibility between the surface to be coated and any solvent(s) used to apply the binder. Other considerations are the environment to which the coating will be exposed after it is applied. Binders of the present disclosure provide resistance to a broad variety of chemical and ultraviolet light exposure (e.g., fluoropolymers such as in the LUMIFLON family of coatings are resistant to UV and light exposure from sunlight).

Durable HP/OP coatings formed with binders can have a broad range of thicknesses. In some embodiments the coatings will have a thickness in a range selected from about 10 microns to about 225 microns; about 15 microns to about 200 microns; about 20 microns to about 150 microns; about 30 microns to about 175 microns; or about 50 microns to about 200 microns.

### 2.1 Lacquer Binders

Lacquer binders typically are polymeric materials that are suspended or dissolved in carrier solvents and which dry to a hard finish, at least in part, by evaporation of the carrier solvents used to apply them. The polymeric binders present in lacquers include, but are not limited to, nitrocellulose and acrylic lacquers; each of which are suitable for use in preparing durable hydrophobic coatings.

In an embodiment, hydrophilic lacquers may be employed as binders; particularly where the coating will be given an application of a silanizing agent after it has been applied to the substrate. In another embodiment, lacquers that are hydrophobic or superhydrophobic as applied in the absence of first or second particles described below may be employed to prepare the coatings described herein.

In addition to the polymeric materials and solvents present in lacquers, a variety of other materials that enhance the properties of lacquers may be present. Such materials can provide not only color but also increased adhesion between the lacquer and the substance upon which it is applied.

A variety of commercial lacquer preparation may be used to prepare the durable coatings described herein. Among the commercial acrylic lacquers that may be employed are "Self-Etching Primer" (Eastwood Co. Pottstown, Pa.); Dupont VariPrime 615S (Dupont Performance Coatings, Wilmington, Del.) and Nason 491-17 Etch Primer (Dupont Performance Coatings Wilmington, Del.)

Lacquers may be used on a variety of surfaces and are particularly useful in forming coatings on plastics, woods and metals, including, but not limited to, steel, stainless steel, and aluminum.

### 2.2 Polyurethane Binders

Polyurethanes are polymers consisting of a chain of organic units joined by urethane (carbamate) linkages. Polyurethane polymers are typically formed through polymerization of at least one type of monomer containing at least two isocyanate functional groups with at least one other monomer containing at least two hydroxyl (alcohol) groups. A catalyst may be employed to speed the polymerization reaction. Other components may be present in the polyurethane coating compositions including, but not limited to, surfactants and other additives that bring about the carbamate forming reaction(s) yielding a coating of the desired properties in a desired cure time.

In some embodiments, the polyurethane employed in the durable coatings may be formed from a polyisocyanate and a mixture of —OH (hydroxyl) and NH (amine) terminated monomers. In such systems the polyisocyanate can be a trimer or homopolymer of hexamethylene diisocyanate, see e.g., FIG. 14.

Some solvents compatible with such systems include n-butyl acetate, toluene, xylene, ethyl benzene, cyclohexanone, isopropyl acetate, and methyl isobutyl ketone and mixtures thereof.

A wide variety of polyurethanes may be used to prepare the durable HP/OP coatings described herein. In some embodiments, polyurethanes that are hydrophobic or superhydrophobic as applied in the absence of first or second particles described below may be employed to prepare the coatings described herein. Among the commercial polyurethanes that may be employed are the POLANE® family of polyurethanes from Sherwin Williams (Cleveland, Ohio).

Polyurethanes may come as a single component ready to apply composition or as a two or three part (component) system, as is the case with POLANE products. For example POLANE B can be prepared by mixing POLANE® B (typically six parts), to catalyst (e.g., typically one part of V66V27 or V66V29 from Sherwin Williams), and a reducer (typically 25-33% of R7K84 from Sherwin Williams) The "pot life" of mixed POLANE® B prepared in that manner is typically 6-8 h.

Polyurethane coatings are compatible with, and show good adhesion to, a wide variety of surfaces. Using polyurethane binders durable HP/OP coatings may be formed on virtually any surface, including but not limited to, those of metals, glass, ceramics, concrete, wood, and plastics.

### 2.3 Fluoropolymer Binders

Fluoropolymers are polymers comprising one or more fluoroalkyl groups. In some embodiments, the fluoropolymers employed in the durable coatings may be formed from Fluoroethylene/vinyl ether copolymer (FEVE).

A wide variety of fluoropolymer coatings may be used to prepare the durable HP/OP coatings described herein. Fluoropolymers that are hydrophobic or superhydrophobic as applied in the absence of first or second particles, which are described further below, may be employed to prepare the coatings described herein. Among the commercial fluoropolymers that may be employed to prepare HP/OP coatings are LUMIFLON® family polymers (Asahi Glass Co., Tokyo, Japan).

Fluoropolymers that may be employed as binders typically come as a two or three component system, as is the case with LUMIFLON® products. For example LUMIFLON® LF can be prepared by mixing 58 parts of LUMIFLON® LF-200, 6.5 parts of DESMODUR® N3300A, (Bayer Material Sciences,) 2.5 parts of catalyst (DABCO T12 (1/10,000 part), DABCO (1,4-diazabicyclo[2.2.2]octane, 1/10,000 part), 1 part xylene), with 33 parts xylene. Unless otherwise noted, references to LUMIFLON®, particularly in the Examples, refer to LUMIFLON® LF.

Fluoropolymer coatings such as LUMIFLON® can be applied to variety of surfaces including wood, metal and concrete. Many fluoropolymers offer resistance to UV light and can therefore be used in exterior applications where the coatings are exposed to the potentially damaging effects of sunlight.

### 2.4 Powder Coatings

Powder coatings typically are thermoplastic or thermoset coatings that are applied on surfaces (often metal) to give a variety of desirable characteristics (e.g., colorful and slick appearance and functionalities such as corrosion protection, etc.). Powder coatings can be applied by a variety of means, including electrostatic spraying of thermoplastic or thermoset powders onto substrate surfaces. Once applied to the surface, the powder coats are subject to thermal treatment at nominal temperatures (about 400° F. or 200° C.), which melt the polymers, permitting their polymerization. The melting and

solidification occur quickly, resulting in the formation of a very tenacious and durable continuous coating. Powder coat materials can be used as binders for the formation of super-hydrophobic, hydrophobic, or oleophobic coatings.

In some embodiments the powder coating is mixed with first particles, at the time the coating is applied to the substrate. First particles may be present in a range that is about 5% to 40%, or 10% to 30%, 10% to 35%, 15% to 30%, or 20% to 40% by weight. In one embodiment, the first particles mixed with the powder coat are Extendspheres (P.A. Industries, Inc., Chatanooga, Tenn.), which may be used at 10% to 30% by weight.

### 2.5 Binders and Durable Hydrophobic, Superhydrophobic and Oleophobic Compositions Applied by Thermal Spray Processes

In addition to the preparation of durable HP/OP coatings using polymeric binders to form attachments between substrates and second particles (e.g., fumed silica nanoparticles) that are capable of forming linkages to moieties that impart one or more of hydrophobic, oleophobic or anti-icing properties (e.g., alkyl, fluoroalkyl, or perfluoroalkyl moieties), it is possible to prepare durable HP/OP coatings using thermal spray processes.

Thermal spray processes permit the formation of durable HP/OP coatings in which it is possible to immobilize materials capable of directly or indirectly forming linkages to chemical groups imparting HP/OP behavior to the surface (e.g., silica or alumina particles capable of binding alkyl, fluoroalkyl, or perfluoro alkyl moieties upon silanization). In an embodiment, particles impregnated into the surface with thermal spray coating can be particles of carbides, metal oxides, or oxides of metalloids (e.g., B, Si, Sb, Te and Ge) such as silicates (e.g., fumed silica). The particles may be directly impregnated into the surface by employing thermal spray processes

In addition, thermal spray processes also permit the formation and immobilization of materials that can be modified to

give the surface OH/OP properties (e.g., the formation of metal oxides bound to, or incorporated into, the surface of a coating applied by an oxidizing thermal spray process). By way of example, thermal spray processes include High-Velocity OxyFuel (HVOF), thermal spray, and Twin-Arc spray (e.g., methods using a ROKIDE® ceramic spray systems). In each case, it is the thermal energy that either bonds particles of metals, alloys, oxide, carbides or nitrides, or a combination of them to metallic substrates. When metals and alloys are sprayed by thermal processes, because of the high temperatures involved and the presence of air or oxygen in the environment, the top layer of the deposited metals and alloys typically is oxidized. The oxidized materials (e.g., metals) may be used to attach moieties providing HP/OP properties (e.g., by reaction with silanizing agents such as compounds of formula (I), SIT8174.0 and the like).

### 3.0 FIRST PARTICLES

While durable coatings employ binders as a means of immobilizing second particles (e.g., nanoparticles) bearing hydrophobic moieties to the surfaces, first particles may advantageously be added to the binder composition to, among other things, improve the durability of the hydrophobic coatings. A wide variety of first particles (also known as extenders or fillers) may be added to the binder to alter the properties and improve coating durability over coating compositions made in their absence. First particles that may be employed in the durable SP/OP coatings include, but are not limited to, particles comprising: wood (e.g., wood dust), glass, metals (e.g., iron, titanium, nickel, zinc, tin), alloys of metals, metal oxides, metalloid oxides (e.g., silica), plastics (e.g., thermoplastics), carbides, nitrides, borides, spinels, diamond, and fibers (e.g., glass fibers). Some commercially available first particles that may be employed in the formation of the durable HP/OP coatings described herein include those in the accompanying Table I.

TABLE I

First Particles Fillers, their particle sizes, properties, and sources.

1	K1	Glass Bubbles	General Purpose Series	0.125	30-120	White	250 3M™	St. Paul, MN
2	K15	Glass Bubbles	General Purpose Series	0.15	30-115	White	300 3M™	St. Paul, MN
3	S15	Glass Bubbles	General Purpose Series	0.15	25-95	White	300 3M™	St. Paul, MN
4	S22	Glass Bubbles	General Purpose Series	0.22	20-75	White	400 3M™	St. Paul, MN
5	K20	Glass Bubbles	General Purpose Series	0.2	20-125	White	500 3M™	St. Paul, MN
6	K25	Glass Bubbles	General Purpose Series	0.25	25-105	White	750 3M™	St. Paul, MN
7	S32	Glass Bubbles	General Purpose Series	0.32	20-80	White	2000 3M™	St. Paul, MN
8	S35	Glass Bubbles	General Purpose Series	0.35	10-85	White	3000 3M™	St. Paul, MN
9	K37	Glass Bubbles	General Purpose Series	0.37	20-85	White	3000 3M™	St. Paul, MN
10	S38	Glass Bubbles	General Purpose Series	0.38	15-85	White	4000 3M™	St. Paul, MN
11	S38HS	Glass Bubbles	General Purpose Series	0.38	15-85	White	5500 3M™	St. Paul, MN
12	K46	Glass Bubbles	General Purpose Series	0.46	15-80	White	6000 3M™	St. Paul, MN
13	S60	Glass Bubbles	General Purpose Series	0.6	15-65	White	10000 3M™	St. Paul, MN
14	S60/HS	Glass Bubbles	General Purpose Series	0.6	11-60	White	18000 3M™	St. Paul, MN
15	A16/500	Glass Bubbles	Floated Series	0.16	35-135	White	500 3M™	St. Paul, MN
16	A20/1000	Glass Bubbles	Floated Series	0.2	30-120	White	1000 3M™	St. Paul, MN
17	H20/1000	Glass Bubbles	Floated Series	0.2	25-110	White	1000 3M™	St. Paul, MN
18	D32/4500	Glass Bubbles	Floated Series	0.32	20-85	White	4500 3M™	St. Paul, MN
19	H50/10000 EPX	Glass Bubbles	Floated Series	0.5	20-60	White	10000 3M™	St. Paul, MN
20	iMK	Glass Bubbles	Floated Series	0.6	8.6-26.7	White	28000 3M™	St. Paul, MN
21	G-3125	Z-Light Spheres™	Ceramic Microspheres	0.7	50-125	Gray	2000 3M™	St. Paul, MN
22	G-3150	Z-Light Spheres™	Ceramic Microspheres	0.7	55-145	Gray	2000 3M™	St. Paul, MN
23	G-3500	Z-Light Spheres™	Ceramic Microspheres	0.7	55-220	Gray	2000 3M™	St. Paul, MN
24	G-600	Zeeospheres™	Ceramic Microspheres	2.3	1-40	Gray	>60,000 3M™	St. Paul, MN
25	G-800	Zeeospheres™	Ceramic Microspheres	2.2	2-200	Gray	>60,000 3M™	St. Paul, MN
26	G-850	Zeeospheres™	Ceramic Microspheres	2.1	12-200	Gray	>60,000 3M™	St. Paul, MN
27	W-610	Zeeospheres™	Ceramic Microspheres	2.4	1-40	White	>60,000 3M™	St. Paul, MN



TABLE I-continued

First Particles Fillers, their particle sizes, properties, and sources.								
28	SG	Extendsphere™	Hollow Spherse	0.72	30-140	Gray	2500	Shpereone Chattanooga, TN
29	DSG	Extendsphere™	Hollow Spherse	0.72	30-140	Gray	2500	Shpereone Chattanooga, TN
30	SGT	Extendsphere™	Hollow Spherse	0.72	30-160	Gray	2500	Shpereone Chattanooga, TN
31	TG	Extendsphere™	Hollow Spherse	0.72	8-75	Gray	2500	Shpereone Chattanooga, TN
32	SLG	Extendsphere™	Hollow Spherse	0.7	10-149	Off White	3000	Shpereone Chattanooga, TN
33	SLT	Extendsphere™	Hollow Spherse	0.4	10-90	Off White	3000	Shpereone Chattanooga, TN
34	SL-150	Extendsphere™	Hollow Spherse	0.62	70	Cream	3000	Shpereone Chattanooga, TN
35	SLW-150	Extendsphere™	Hollow Spherse	0.68	8-80	White	3000	Shpereone Chattanooga, TN
36	HAT	Extendsphere™	Hollow Spherse	0.68	10-165	Gray	2500	Shpereone Chattanooga, TN
37	HT-150	Extendsphere™	Hollow Spherse	0.68	8-85	Gray	3000	Shpereone Chattanooga, TN
38	KLS-90	Extendsphere™	Hollow Spherse	0.56	4-05	Light Gray	1200	Shpereone Chattanooga, TN
39	KLS-125	Extendsphere™	Hollow Spherse	0.56	4-55	Light Gray	1200	Shpereone Chattanooga, TN
40	KLS-150	Extendsphere™	Hollow Spherse	0.56	4-55	Light Gray	1200	Shpereone Chattanooga, TN
41	KLS-300	Extendsphere™	Hollow Spherse	0.56	4-55	Light Gray	1200	Shpereone Chattanooga, TN
42	HA-300	Extendsphere™	Hollow Spherse	0.68	10-146	Gray	2500	Shpereone Chattanooga, TN
43	XIOM 512	Thermoplastic	Modified Polyethylene Resins	0.96	10-100	White	508	XIOM West Babylon, NY
44	XIOM 512	Thermoplastic	Modified Polyethylene Resins	0.96	10-100	Black	508	XIOM Corp West Babylon, NY
45	CORVEL™ BLACK 78-7001	Thermoplastic	Nylon Powder Coating	1.09	44-74	Black		XIOM Corp ROHM & HASS Philadelphia, PA
46	Microglass 3082	Fibers	Microglass milled E-glass Filaments	1.05	16X120	White		Fibertec Bridgewater, MA
47	Microglass 9007D	Fibers Silane Treated	Microglass milled E-glass Filaments	0.53	10X150	White		Fibertec Bridgewater, MA

In addition to the chemical nature of the first particles, other variables may be considered in the selection of first particles. These variables include, but are not limited to, the effect the first particle is expected to have on coatings, their hardness, their compatibility with the binder, the expected resistance of the first particle to the environment in which coating will be employed, and the environment the first particles must endure in the coating process, including resistance to temperature and solvent conditions. For example, where a first particle is applied in a thermoplastic binder that requires heating to cure the coating, the first particle must be capable of withstanding the temperatures required to cure the coating. In another example, where particles are applied to surfaces using a thermal spray process, the particles must be capable of withstanding the temperatures and environment presented in that process.

In an embodiment, first particles have an average size in a range selected from: greater than about 5 microns ( $\mu\text{m}$ ) to about 50  $\mu\text{m}$ ; about 10  $\mu\text{m}$  to about 100  $\mu\text{m}$ ; about 10  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 20  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 30  $\mu\text{m}$  to about 100  $\mu\text{m}$ ; about 30  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 50  $\mu\text{m}$  to about 100  $\mu\text{m}$ ; about 50  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 75  $\mu\text{m}$  to about 150  $\mu\text{m}$ ; about 75  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 100  $\mu\text{m}$  to about 225  $\mu\text{m}$ ; about 125  $\mu\text{m}$  to about 225  $\mu\text{m}$ ; or about 100  $\mu\text{m}$  to about 250  $\mu\text{m}$ .

In another embodiment, first particles have an average size in a range selected from: about 30  $\mu\text{m}$  to about 225  $\mu\text{m}$  (microns); about 30  $\mu\text{m}$  to about 50  $\mu\text{m}$ ; about 30  $\mu\text{m}$  to about 100  $\mu\text{m}$ ; about 30  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 50  $\mu\text{m}$  to about 100  $\mu\text{m}$ ; about 50  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 75  $\mu\text{m}$  to about 150  $\mu\text{m}$ ; about 75  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 100  $\mu\text{m}$  to about 225  $\mu\text{m}$ ; about 100  $\mu\text{m}$  to about 225  $\mu\text{m}$  or about 100  $\mu\text{m}$  to about 250  $\mu\text{m}$ .

First particles may be incorporated into binders at various ratios depending on the binder composition and the first par-

ticle's properties. In some embodiments, the first particles may have a content range selected from: about 1% to about 50%; from about 2% to about 40%; from about 4% to about 30%; from about 5% to about 25%; from about 5% to about 35%; from about 10% to about 25%; from about 10% to about 30%; from about 10% to about 40%; from about 10% to about 45%; from about 15% to about 25%; from about 15% to about 35%; from about 15% to about 45%; from about 20% to about 30%; from about 20% to about 35%; from about 20% to about 40%; from about 20% to about 45%; from about 20% to about 55%; from about 25% to about 40%; from about 25% to about 45%; from about 25% to about 55%; from about 30% to about 40%; from about 30% to about 45%; from about 30% to about 55%; from about 30% to about 60%; from about 35% to about 45%; from about 35% to about 50%; from about 35% to about 60%, or from about 40% to about 60% on a weight basis.

In some embodiments, where the first particles comprises or consist of glass spheres, the first particles may be present in a content range selected from: about 30% to about 40%; from about 30% to about 45%; from about 35% to about 45%; or from about 35% to about 50% on a weight basis. In other embodiments where the first particles are a polyethylene or modified polyethylene, the particle may be present in a content range selected from: 35% to about 45%; from about 35% to about 50%; or from 35% to about 50% on a weight basis.

First particles may have a size range selected from: about 1  $\mu\text{m}$  to about 225  $\mu\text{m}$  (microns); 30  $\mu\text{m}$  to about 225  $\mu\text{m}$  (microns); about 25  $\mu\text{m}$  to about 50  $\mu\text{m}$ ; about 30  $\mu\text{m}$  to about 50  $\mu\text{m}$ ; about 10  $\mu\text{m}$  to about 100  $\mu\text{m}$ ; about 10  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 20  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 30  $\mu\text{m}$  to about 100  $\mu\text{m}$ ; about 30  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 50  $\mu\text{m}$  to about 100  $\mu\text{m}$ ; about 50  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 75  $\mu\text{m}$  to about 150  $\mu\text{m}$ ; about 75  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; or about 100  $\mu\text{m}$  to about 225  $\mu\text{m}$ .

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In one embodiment first particles have an average size in a range selected from: about 1  $\mu\text{m}$  to about 225  $\mu\text{m}$  (microns); greater than about 5  $\mu\text{m}$  to about 50  $\mu\text{m}$ ; about 10  $\mu\text{m}$  to about 100  $\mu\text{m}$ ; about 10  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 20  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 30  $\mu\text{m}$  to about 100  $\mu\text{m}$ ; about 30  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 50  $\mu\text{m}$  to about 100  $\mu\text{m}$ ; about 50  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 75  $\mu\text{m}$  to about 150  $\mu\text{m}$ ; about 75  $\mu\text{m}$  to about 200  $\mu\text{m}$ ; about 100  $\mu\text{m}$  to about 225  $\mu\text{m}$ ; or about 125  $\mu\text{m}$  to about 225  $\mu\text{m}$ . In another embodiment, the coatings may contain first particles in the above-mentioned ranges subject to either the proviso that the coatings do not contain only particles (e.g., first or second particles) with a size of 25 microns or less, or the proviso that the coatings do not contain particles with a size of 25 microns or less.

In another embodiment, first particles have an average size greater than 30 microns and less than 250 microns, and do not contain non-trivial amounts of particles (e.g., first and second particles) with a size of 30 microns or less. And in still another embodiment, the coatings do not contain only particles (e.g., first and second particles) with a size of 50 microns or less, or particles with an average size of 50 microns or less in non-trivial amounts.

The incorporation of first particles can lead to a surface that is textured due to the presence of the first particles. In such embodiments, the presence of the first particles results in a surface texture that has elevations on the level of the coating formed. The height of the elevations due to the presence of the first particles can be from 0 (where the first particle is just below the line of the binders surface) to a point where the first particles are almost completely above the level of the binder coating (although they may still be coated with binder). Thus, the presence of first particles can result in a textured surface wherein the first particles cause elevations in the binder that have maximum heights in a range selected from: from about 10 to about 80 microns; from about 15 to about 80 microns; from about 20 to about 100 microns; from 30 to 70 microns; or from about 1 to 50 microns.

The surface texture of coatings may also be assessed using the arithmetical mean roughness (Ra) or the ten point mean roughness (Rz) as measure of the surface texture. In an embodiment, a coating described herein has an arithmetical mean roughness (Ra) in a range selected from: about 0.2 microns to about 20 microns; from about 0.3 microns to about 18 microns; from about 0.2 microns to about 8 microns; from about 8 microns to about 20 microns; or from about 0.5 microns to about 15 microns. In another embodiment, a coating as described herein has a ten point mean roughness (Rz) in a range selected from: about 1 micron to about 90 microns; from about 2 microns to about 80 microns; from about 3 microns to about 70 microns; from about 1 micron to about 40 microns; from about 40 microns to about 80 microns; from about 10 microns to about 65 microns; or from about 20 microns to about 60 microns.

First particles may optionally comprise moieties that make them hydrophobic or superhydrophobic and/or oleophobic. Where it is desirable to introduce such moieties the particles may be reacted with reagents that covalently bind moieties that make them hydrophobic, superhydrophobic, or oleophobic. In some embodiments, the reagents may be silanizing agents, such as those that introduce alkyl, haloalkyl, fluoroalkyl or perfluoroalkyl moieties (functionalities). In some embodiments the silanizing agents are compounds of formula (I) (i.e.,  $\text{R}_{4-n}\text{Si}-\text{X}_n$ ), and the various embodiments of compounds of formula (I) described below for the treatment of second particles. The surface of many types of first particles can be activated to react with silanizing agents by various

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treatments including exposure to acids, bases, plasma, and the like, where necessary to achieve functionalization of the particles.

In any embodiment described herein, first particles may be employed that do not contain functional groups that impart one or more of hydrophobic, superhydrophobic, and/or oleophobic properties to the particles (e.g., properties beyond the properties inherent to the composition forming the particles). In one such embodiment, first particles do not contain covalently bound alkyl, haloalkyl, fluoroalkyl or perfluoroalkyl functionalities (moieties). In another such embodiment the first particles are not treated with a silanizing agent (e.g., a compound of formula (I)).

#### 4.0 SECOND PARTICLES

A variety of second particles can be used to prepare the durable coatings displaying HP/OP properties. Suitable second particles have a size from about 1 nanometers (nm) to 25 microns and are capable of binding covalently to one or more chemical groups (moieties) that provide the second particles, and the coatings into which they are incorporated, one or more of hydrophobic, oleophobic and anti-icing properties.

In some embodiments the second particles may have an average size in a range selected from about 1 nm to about 100 nm; about 10 nm to about 200 nm; about 20 nm to about 400 nm; about 10 nm to 500 nm; about 40 nm to about 800 nm; about 100 nm to about 1 micron; about 200 nm to about 1.5 microns; about 500 nm to about 2 microns; about 500 nm to about 2.5 microns; about 1.0 micron to about 10 microns; about 2.0 microns to about 20 microns; about 2.5 microns to about 25 microns; about 500 nm to about 25 microns; about 400 nm to about 20 microns; or about 100 nm to about 15 microns.

In one embodiments, such as where the second particles are prepared by fuming (e.g., fumed silica or fumed zinc oxide), the second particles may have an average size in a range selected from about 1 nm to about 50 nm; about 1 nm to about 100 nm; about 1 nm to about 400 nm; about 1 nm to about 500 nm; about 2 nm to about 120 nm; about 5 nm to about 150 nm; about 5 nm to about 400 nm; about 10 nm to about 300 nm; or about 20 nm to 400 nm.

Second particles having a wide variety of compositions may be employed in the durable coatings described herein. In some embodiments the second particles will be particles of metal oxides (e.g., aluminum oxides, zinc oxides, nickel oxide, zirconium oxides, iron oxides, or titanium dioxide) such as alumina, or oxides of metalloids (e.g., oxides of B, Si, Sb, Te and Ge) such as silicates (e.g., fumed silica) or particles comprising one or more metal oxides, oxides of metalloids or combination thereof, such as second particles of glasses. The particles are treated to introduce one or more moiety (group) that imparts HP/OP properties to the particles either prior to incorporation into the compositions that will be used to apply coatings or after they are incorporated into the coatings. In one embodiment, second particles are treated with silanizing agents to incorporate groups that will give the particles HP/OP properties.

In one embodiment second particles are silica (silicates), alumina (e.g.,  $\text{Al}_2\text{O}_3$ ), a titanium oxide, or zinc oxide, that are optionally treated with a silanizing agent.

In another embodiment, the second particles are comprised of fumed silica; and in a further embodiment, the second particles are comprised of fumed silica and have an average size in the range of 1 nm to 100 nm or 2 nm to 200 nm; wherein the silica is optionally treated with a silanizing agent.

In yet another embodiment second particles are comprised of one or more metals, metal oxides (e.g., zinc oxide, titanium dioxide,  $\text{Al}_2\text{O}_3$ ), metalloids (e.g., B, Si, Sb, Te and Ge), oxides of a metalloid (e.g.,  $\text{SiO}_2$  and silicates), or glasses. In such an embodiment the one or more independently selected second particles have average sizes in ranges independently (separately) selected from about 1 nm to about 100 nm; about 10 nm to about 200 nm; about 20 nm to about 400 nm; about 10 nm to 500 nm; about 40 nm to about 800 nm; about 100 nm to about 1 micron; about 200 nm to about 1.5 microns; about 500 nm to about 2 microns; about 500 nm to about 2.5 microns; about 1.0 micron to about 10 microns; about 2.0 microns to about 20 microns; about 2.5 microns to about 25 microns; about 500 nm to about 25 microns; about 400 nm to about 20 microns; or about 100 nm to about 15 microns. Second particles in such an embodiment may be employed in coatings prepared using thermal spray processes.

In any of the above-mentioned embodiments, the lower size of second particles may be limited to particles greater than 20 nm, 25 nm, 30 nm, 35 nm, 40 nm, 45 nm, 50 nm, or 60 nm. Similarly, in any of the above-mentioned embodiments, the upper size of second particles may be limited to particles less than 20, 10, 5, 1, 0.8, 0.6, 0.5, 0.4, 0.3 or 0.2 microns. Limitation on the upper and lower size of second particles may be used alone or in combination with any of the above-recited size limits on particle composition, percent composition in the coatings, etc.

#### 4.1 Hydrophobic and Oleophobic Components of Second Particles

Second particles employed in the preparation of the durable coatings described herein comprise one or more independently selected chemical groups (moieties or functionalities) that impart HP/OP properties to provide the second particles, and the coatings into which they are incorporated. Second particles typically will be treated with agents that introduce such moieties before being incorporated into the durable coatings described herein, however, it is also possible to treat the coating after it is applied to a surface with agents that modify the second particles and introduce or more of hydrophobic, superhydrophobic or oleophobic properties. In such circumstances, other components of the coating (e.g., the binder or first particles) may also become modified by the agent.

In some embodiments, the second particles will be treated with an agent that introduces one or more hydrophobic, superhydrophobic or oleophobic properties.

In another embodiment the second particles will bear one or more alkyl, haloalkyl, fluoroalkyl, and perfluoroalkyl moieties. Such moieties can be covalently bound directly or indirectly bound to the second particle, such as through one or more intervening silicon or oxygen atoms.

In still another embodiment the second particles will bear one or more alkyl, fluoroalkyl, and perfluoroalkyl moieties of the formula  $\text{R}_{4-n}\text{Si}-$ , where n is from 1-3, that are directly or indirectly bound (e.g., covalently bound) to the second particle, such as through one or more intervening atoms.

##### 4.1.1 The Use of Silanizing Agents

A variety of silanizing agents can be employed to introduce  $\text{R}_{4-n}\text{Si}-$  moieties into second particles prior or subsequent to their introduction into the durable coatings described herein. Suitable silanizing agents have both leaving groups and terminal functionalities. Terminal functionalities are groups that are not displaced by reaction of a silanizing agent with silica second particles (e.g., R groups of compounds of the formula (I)). Leaving groups are those groups that are displaced from silanizing agents upon reaction to form bonds with the second particles.

Prior to reacting first or second particles with silanizing agents, the particles may be treated with an agent that will increase the number of sites available for reaction with the silanizing agent (e.g.,  $\text{SiCl}_4$ ,  $\text{SiCl}_4$ ,  $\text{Si}(\text{OMe})_4$ ,  $\text{Si}(\text{OEt})_4$ ,  $\text{SiCl}_3\text{CH}_3$ ,  $\text{SiCl}_3\text{CH}_2\text{SiCl}_3$ ,  $\text{SiCl}_3\text{CH}_2\text{CH}_2\text{SiCl}_3$ ,  $\text{Si}(\text{OMe})_3\text{CH}_2\text{Si}(\text{OMe})_3$ ,  $\text{Si}(\text{OMe})_3\text{CH}_2\text{CH}_2\text{Si}(\text{OMe})_3$ ,  $\text{Si}(\text{OEt})_3\text{CH}_2\text{Si}(\text{OEt})_3$ , or  $\text{Si}(\text{OEt})_3\text{CH}_2\text{CH}_2\text{Si}(\text{OEt})_3$  and the like). Treatment with such agents is conducted with a 1% to 5% solution of the agent in a suitable solvent (e.g., hexane), although higher concentrations may be employed (e.g., 5% to 10%). Subsequent reaction with silanizing agents is typically conducted using a silanizing agent at in the range of 1%-2% w/v, although concentrations in the range of 2%-5% w/v may also be used. Depending on the reagents employed, the reaction, which can be conducted at room temperature, can be typically conducted for 1 hour to 6 hours, although reaction for as long as 24 hours may be desirable in some instances.

In one embodiment, silanizing agents are compounds of the formula (I):



where n is an integer from 1-3;

each R is independently selected from

- (i) alkyl or cycloalkyl group optionally substituted with one or more fluorine atoms,
- (ii)  $\text{C}_{1 \text{ to } 20}$  alkyl optionally substituted with one or more independently selected substituents selected from fluorine atoms and  $\text{C}_{6-14}$  aryl groups, which aryl groups are optionally substituted with one or more independently selected halo,  $\text{C}_{1 \text{ to } 10}$  alkyl,  $\text{C}_{1 \text{ to } 10}$  haloalkyl,  $\text{C}_{1 \text{ to } 10}$  alkoxy, or  $\text{C}_{1 \text{ to } 10}$  haloalkoxy substituents,
- (iii)  $\text{C}_{6 \text{ to } 20}$  alkyl ether optionally substituted with one or more substituents independently selected from fluorine and  $\text{C}_{6-14}$  aryl groups, which aryl groups are optionally substituted with one or more independently selected halo,  $\text{C}_{1 \text{ to } 10}$  alkyl,  $\text{C}_{1 \text{ to } 10}$  haloalkyl,  $\text{C}_{1 \text{ to } 10}$  alkoxy, or  $\text{C}_{1 \text{ to } 10}$  haloalkoxy substituents,
- (iv)  $\text{C}_{6-14}$  aryl, optionally substituted with one or more substituents independently selected from halo or alkoxy, and haloalkoxy substituents;
- (v)  $\text{C}_{4 \text{ to } 20}$  alkenyl or  $\text{C}_{4 \text{ to } 20}$  alkynyl, optionally substituted with one or more substituents independently selected from halo, alkoxy, or haloalkoxy; and
- (vi)  $\text{Z}-((\text{CF}_2)_q(\text{CF}_3))_r$ , wherein Z is a  $\text{C}_{1-12}$  divalent alkane radical or a  $\text{C}_{2-12}$  divalent alkene or alkyne radical, q is an integer from 1 to 12, and r is an integer from 1-4;

each X is independently selected from  $-\text{H}$ ,  $-\text{Cl}$ ,  $-\text{I}$ ,  $-\text{Br}$ ,  $-\text{OH}$ ,  $-\text{OR}^2$ ,  $-\text{NHR}^3$ , or  $-\text{N}(\text{R}^3)_2$ ;

each  $\text{R}^2$  is independently selected  $\text{C}_{1 \text{ to } 4}$  alkyl or haloalkyl group; and

each  $\text{R}^3$  is independently an independently selected H,  $\text{C}_{1 \text{ to } 4}$  alkyl or haloalkyl group.

In one embodiment, R is an alkyl or fluoroalkyl group having from 6 to 20 carbon atoms.

In another embodiment, R is an alkyl or fluoroalkyl group having from 8 to 20 carbon atoms.

In another embodiment, R is an alkyl or fluoroalkyl group having from 10 to 20 carbon atoms.

In another embodiment, R is an alkyl or fluoroalkyl group having from 6 to 20 carbon atoms and n is 3

In another embodiment, R is an alkyl or fluoroalkyl group having from 8 to 20 carbon atoms and n is 3

In another embodiment, R is an alkyl or fluoroalkyl group having from 10 to 20 carbon atoms and n is 3.

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In another embodiment, R has the form  $\text{—Z—}((\text{CF}_2)_q(\text{CF}_3)_r)$ , wherein Z is a  $\text{C}_{1-12}$  divalent alkane radical or a  $\text{C}_{2-12}$  divalent alkene or alkyne radical, q is an integer from 1 to 12, and r is an integer from 1-4.

In any of the previously mentioned embodiments of compounds of formula (I) the value of n may be varied such that 1, 2 or 3 independently selected terminal functionalities are present in compounds of formula (I). In one embodiment, n is 3. In another embodiment, n is 2, and in still another embodiment n is 1.

In any of the previously mentioned embodiments of compounds of formula (I), all halogen atoms present in any one or more R groups may be fluorine atoms in some embodiments.

In any of the previously mentioned embodiments of compounds of formula (I), X may be independently selected from H, Cl,  $\text{—OR}^2$ ,  $\text{—NHR}^3$ ,  $\text{—N(R}^3)_2$ , or combinations thereof in some embodiments. In another, embodiment, X may be selected from Cl,  $\text{—OR}^2$ ,  $\text{—NHR}^3$ ,  $\text{—N(R}^3)_2$ , or combinations thereof. In still another embodiment, X may be selected from, Cl,  $\text{—NHR}^3$ ,  $\text{—N(R}^3)_2$  or combinations thereof.

Any durable coating described herein may be prepared with one, two, three, four or more compounds of formula (I) employed alone or in combination to modify the first or second particle, and or other components of the coating (e.g., first particles and binder).

The use of silanizing agents of formula (I) to modify first or second particles or any of the other components of the coatings or coating compositions will introduce one or more  $\text{R}_{3-n}\text{X}_n\text{Si—}$  groups (e.g.,  $\text{R}_3\text{Si—}$ ,  $\text{R}_2\text{X}_1\text{Si—}$ , or  $\text{RX}_2\text{Si—}$  groups) where R and X are as defined for a compound of formula (I), n is 0, 1, or 2 (due to the displacement of at least one “X” substituent and formation of a bond between the particle and the Si atom), and the bond with the particle is the silicon atom is indicated by a dash “—” (e.g.,  $\text{R}_3\text{Si—}$ ,  $\text{R}_2\text{X}_1\text{Si—}$ , or  $\text{RX}_2\text{Si—}$  groups).

In another embodiment, specific reagents that can be employed to prepare first or second particles with hydrophobic, superhydrophobic, or oleophobic properties include silanizing agents (e.g., compounds that are commercially available from Gelest, Inc., Morrisville, Pa.). Such silanizing agents include, but are not limited to, the following compounds, which are identified by their chemical name followed by the commercial supplier reference number (e.g., their Gelest reference in parentheses): (tridecafluoro-1,1,2,2-tetrahydrooctyl)silane (SIT8173.0); (tridecafluoro-1,1,2,2-tetrahydrooctyl)trichlorosilane (SIT8174.0); (tridecafluoro-1,1,2,2-tetrahydrooctyl)triethoxysilane (SIT8175.0); (tridecafluoro-1,1,2,2-tetrahydrooctyl)trimethoxysilane (SIT8176.0); (heptadecafluoro-1,1,2,2-tetrahydrodecyl)dimethyl(dimethylamino)silane (SIH5840.5); (heptadecafluoro-1,1,2,2-tetrahydrodecyl)tris(dimethylamino)silane (SIH5841.7); n-octadecyltrimethoxysilane (SI06645.0); n-octyltriethoxysilane (SI06715.0); and nonafluorohexyldimethyl(dimethylamino)silane (SIN6597.4).

The two attributes of silanizing agents important for the purposes of forming suitable first or second particles are the leaving group (e.g., X groups of compounds of the formula (I)) and the terminal functionality (e.g., R groups of compounds of the formula (I)). Silanizing agent leaving groups determine the reactivity of the agent with the first or second particle. Where, the first or second particles are a silicate (e.g., fumed silica) the leaving group can be displaced to form  $\text{Si—O—Si}$  bonds. The terminal functionality determines the level of hydrophobicity that results from application of the silane to the surface. Leaving group effectiveness is ranked in the decreasing order as chloro>methoxy>hydro (H)>ethoxy

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(measured as trichloro>trimethoxy>trihydro>triethoxy). This ranking of the leaving groups is consistent with their bond dissociation energy.

In addition to the silanizing agents recited above, a variety of other silanizing agents can be used to alter the properties of first or second particles and to provide hydrophobic, superhydrophobic or oleophobic properties. In some embodiments second particles may be treated with an agent selected from dimethyldichlorosilane, hexamethyldisilazane, octyltrimethoxysilane, polydimethylsiloxane, or tridecafluoro-1,1,2,2-tetrahydrooctyl trichlorosilane. In further embodiments, the first or second particles are silica second particles. Silica second particles treated with such agents may have an average size in a range selected from: about 1 nm to about 50 nm; about 1 nm to about 100 nm; about 1 nm to about 400 nm; about 1 nm to about 500 nm; about 2 nm to about 120 nm; about 5 nm to about 150 nm; about 5 nm to about 400 nm; about 10 nm to about 300 nm; about 20 nm to 400 nm; or about 50 nm to 250 nm.

In addition to the silanizing agents recited above, which can be used to modify any one or more components of coatings (e.g., first and/or second particles) other silanizing agents can be employed including, but not limited to, one or more of: gamma-aminopropyltriethoxysilane, Dynasylan® A (tetraethylorthosilicate), hexamethyldisilazane, and Dynasylan® F 8263 (fluoroalkylsilane), any one or more of which may be used alone or in combination with any other silanizing agent recited herein.

A variety of agents can be employed to introduce hydrophobic or oleophobic behavior into the coatings described herein. However, the use of agents to introduce alkyl functionalities (e.g., silanizing agents) does not generally prove as effective as their fluorinated or perfluorinated counterparts. The introduction of fluorinated or perfluorinated functionalities typically produce surfaces with the highest hydrophobicity.

#### 4.1.3 Use of Compounds Other than Silanizing Agents

Other agents t can be used to introduce hydrophobic, superhydrophobic or oleophobic moieties into second particles. The choice of such agents will depend on the functionalities available for forming chemical (covalent) linkages between hydrophobic/oleophobic component and the functional groups present on the second particles surface. For example, where second particle surfaces have, or can be modified to have, hydroxyl or amino groups, then acid anhydrides and acid chlorides of alkyl, fluoroalkyl, and perfluoroalkyl compounds may be employed (e.g., the acid chlorides:  $\text{Cl—C(O)(CH}_2)_{4-18}\text{CH}_3$ ;  $\text{Cl—C(O)(CH}_2)_{4-10}(\text{CF}_2)_{2-14}\text{CF}_3$ ;  $\text{Cl—C(O)(CF}_2)_{4-18}\text{CF}_3$  or the anhydrides of those acids).

#### 4.1.4 Preparation of Surfaces with Oleophobic Properties.

In addition to the hydrophobicity displayed against aqueous based solutions, suspension, and emulsions, and the anti-icing properties of the coatings described herein, the coatings described herein also have the ability to display oleophobic behavior. This is true particularly where the coatings comprise fluorinated or perfluorinated alkyl groups (e.g., where the terminal functionality, that is the R group(s) of a silane of the formula  $\text{R}_{4-n}\text{Si—X}_n$  are fluorinated alkyl or perfluoroalkyl. Coatings comprising fluorinated or perfluorinated alkyl groups (e.g., as functionalities on second particles) can also be used to form spill-resistant borders that display the ability to retain oils, lipids and the like.

#### 4.1.5 Sources of Second Particles

Second particles such as fumed silica may be purchased from a variety of suppliers, including but not limited to: Cabot Corp., Billerica, Mass. (e.g., Nanogel TLD201, CAB-O-SIL® TS-720, and M5 (untreated silica)); Evonik Industries,

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Essen, Germany (e.g., ACEMATT® silica such as untreated HK400, AEROXIDE® TiO<sub>2</sub> titanium dioxide, AEROXIDE® alumina).

Some commercially available second particles are set forth in the accompanying scheme.

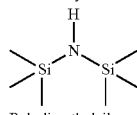
CAB-O-SIL Grade	Surface Treatment	Level of Treatment	Nominal BET Surface Area of Base Silica (m <sup>2</sup> /g)
M-5	None	None	200
TS-610	Dimethyldichlorosilane <sup>b</sup>	Intermediate	130
TS-530	Hexamethyldisilazane <sup>b</sup>	High	320
TS-382	Octyltrimethoxysilane <sup>b</sup>	High	200
TS-720	Polydimethylsiloxane <sup>b</sup>	High	200

<sup>a</sup>Data from Cabot Corp. website.

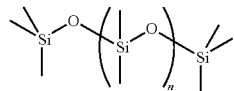
Dimethyldichlorosilane



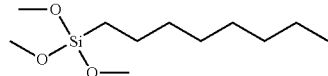
Hexamethyldisilazane



Polydimethylsiloxane



Octyltrimethoxysilane



As purchased the second particles may be untreated (e.g., M5 silica) and may not possess any HP/OP properties. Such untreated particles can be treated to covalently attach one or more groups or moieties to the particles that give them HP/OP properties with, for example, silanizing agents discussed above.

## 5.0 SUBSTRATES

Durable hydrophobic/superhydrophobic coatings can be applied to any surface to which a binder can adhere. The surfaces may be flexible or rigid. In some embodiments the surface can be made from a material selected from glass, metal, metalloid, ceramic, wood, plastic, resin, rubber, stone, concrete or a combination thereof. In another embodiment the surface may be made from a material selected from the group consisting of glass, ceramic and a combination thereof. In other embodiments, the surfaces may be comprised of metalloids (e.g., B, Si, Sb, Te and Ge).

Any glass can be employed as a substrate for durable hydrophobic or superhydrophobic coatings including, without limitation: soda lime glass, borosilicate glass, sodium borosilicate glass, aluminosilicate glass, aluminoborosilicate glass, optical glasses, lead crystal glass, fused silica glass, germania glasses, and germanium selenide glasses, and combinations thereof.

Any metal can be employed as a substrate for durable hydrophobic or superhydrophobic coatings including, without limitation: iron, nickel, chrome, copper, tin, zinc, lead, magnesium, manganese, aluminum, titanium silver, gold, and platinum or combinations thereof, or alloys comprising those

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metals. In one embodiment, the metal forming the surface comprises steel or stainless steel. In another embodiment, the metal used for the surface is chromium, is plated with chromium, or comprises chromium or a chromium coating.

Any ceramic can be employed as a substrate for durable hydrophobic or superhydrophobic coatings including, without limitation: earthenware (typically quartz and feldspar), porcelain (e.g., made from kaolin), bone china, alumina, zirconia, and terracotta. For the purpose of this disclosure, a glazing on a ceramic may be considered either as a ceramic or a glass.

Any wood can be employed as a substrate for durable hydrophobic or superhydrophobic coatings including, without limitation, hard and soft woods. In some embodiments, woods may be selected from alder, poplar, oak, maple, cherry, apple, walnut, holly, boxwood, mahogany, ebony, teak, luan, and elm. In other embodiments woods may be selected from ash, birch, pine, spruce, fir, cedar, and yew.

Any plastic or resin can be employed as a substrate for durable hydrophobic or superhydrophobic coatings including, without limitation polyolefins (such as a polypropylene and polyethylene), a polyvinylchloride plastics, a polyamides, a polyimides, a polyamideimides, a polyesters, aromatic polyesters, polycarbonates, polystyrenes, polysulfides, polysulfones, polyethersulfones, polyphenylenesulfides, a phenolic resins, polyurethanes, epoxy resins, a silicon resins, acrylonitrile butadiene styrene resin/plastic, methacrylic resins/plastics, acrylate resins, polyacetals, polyphenylene oxides, polymethylpentenes, melamines, alkyd resins, polyesters or unsaturated polyesters, polybutylene terephthalates, combinations thereof, and the like.

Any rubber can be employed as a substrate for durable hydrophobic or superhydrophobic coatings including, without limitation: styrene-butadiene rubber, butyl rubber, nitrile rubber, chloroprene rubber, polyurethane rubber, silicon rubber, and the like.

Any type of stone, concrete, or combination thereof can be employed as a substrate for durable hydrophobic or superhydrophobic coatings including, without limitation, igneous, sedimentary and metamorphic stone (rock). In one embodiment the stone is selected from granite, marble, limestone, hydroxylapatite, quartz, quartzite, obsidian and combinations thereof. Stone may also be used in the form of a conglomerate with other components such as concrete and/or epoxy to form an aggregate that may be used as a surface upon which a durable hydrophobic coating may be applied.

## 6.0 APPLICATION OF COATINGS TO SUBSTRATES

The coatings described herein can be applied to surfaces using any means known in the art, including but not limited to, brushing, painting, printing, stamping, rolling, dipping, spin-coating, spraying, or electrostatic spraying. Generally, the surfaces will be rigid or semi-rigid, but the surfaces can also be flexible, for example in the instance of wire and tapes or ribbons.

The coatings described herein can be applied to virtually any substrate to provide HP/OP properties. The choice of coatings and coating process that will be used may be affected by the compatibility of the substrate and its surface to the coating process and the component of the coating compositions. Among the considerations are the compatibility of the substrate and its surface with any solvents that may be employed in the application of the coatings and the ability of a desired coating to adhere to the substrate's surface. In addition, where the coating process will expose the substrate, and

especially its surface, to heating (e.g., where binders are thermoplastics, thermoset plastics, or where thermal spraying is employed) the ability to withstand the effects of temperature are considerations that must be taken into account.

Coatings may take any desired shape or form, limited only by the manner and patterns in which they can be applied. In some embodiments, the coating will completely cover a surface. In other embodiments the coatings will cover only a portion of a surface, such as one or more of a top, side or bottom of an object. In one embodiment, a coating is applied as a line or strip on a substantially flat or planar surface. In such an embodiment the line or strip may form a spill-resistant border (see e.g., Example 18).

The shape, dimensions and placement of coatings on surfaces can be controlled by a variety of means including the use of masks which can control not only the portions of a surface that will receive a coating, but also the portions of a surface that may receive prior treatments such as the application of a primer layer or cleaning by abrasion or solvents. For example, where sand blasting or a chemical treatment is used to prepare a portion of a surface for coating, a mask resistant to those treatments would be selected (e.g., a mask such as a rigid or flexible plastic, resin, or rubber/rubberized material). Masking may be attached to the surface through the use of adhesives, which may be applied to the mask agent, the surface, or both.

In another embodiment a coatings applied to a ribbon, tape or sheet that may then be applied to a substrate by any suitable means including adhesive applied to the substrate, the ribbon or tape, or both. Ribbons, tapes and sheets bearing a superhydrophobic coating may be employed in a variety of application, including forming spill proof barriers on surfaces (see e.g., Example 18). Ribbons, tapes, and sheets of coated material may be made from any flexible substrate. Ribbons, tapes, and sheets are generally formed of a substantially flat (planar) flexible material where one side (the top) is made hydrophobic or superhydrophobic. This includes metal tapes such as aluminum tape or other tapes (e.g., metal adhesive tape, plastic adhesive tape, paper adhesive tape, fiber glass adhesive tapes), wherein one side is coated with an HP/OP coating and adhesive on the other side. Such ribbons, tapes, and sheets can be applied to any type of surface including metal, ceramic, glass, plastic, or wood surfaces, for a variety of purposes.

To improve the adherence of coatings to a surface, the surface may be treated or primed such as by abrasion, cleaning with solvents or the application of one or more undercoatings of primers. In some embodiments where metals can be applied to surfaces (e.g., by electroplating, vapor deposition, or dipping) and it is deemed advantageous, surfaces maybe coated with metals prior to the application of a coating described herein.

#### 6.1 One-Step Coating Applications

In some embodiments, the coatings may be applied using methods wherein binder, first particles, and second particles are mixed prior to the application of the coating composition to the surface. For the purpose of this disclosure, such methods are termed one-step methods or processes.

In one embodiment, a one-step process of applying a coating to a substrate may comprise:

applying to the substrate a coating composition comprising (i) a binder; (ii) first particles having a size of about 30 microns to about 225 microns; and (iii) second particles having a size of about 1 nanometer to 25 microns and optionally comprising one or more independently selected alkyl, haloalkyl, fluoroalkyl, or perfluoroalkyl groups covalently bound, either directly or indirectly, to

said second particles; wherein said composition optionally contains 5% to 10% of a block copolymer on a weight basis.

In one-step methods the binders, first particles, second particles and silanizing agents described above may be employed. First particles may be less than 30 microns, and may be particles with an average size in the range of about 1  $\mu\text{m}$  to about 225  $\mu\text{m}$  as described above.

In one embodiment, coatings are prepared in a one step process with fumed silica second particles (TS-720), where the second particles are present in the range of 10-15% on a weight basis in the coating. In another embodiment, coatings are prepared in a one step process with fumed silica second particles treated with SIT8174, where the second particles are present in the range of 10-15% on a weight basis in the coating. In such embodiments, prior to treatment with silanizing agents such as SIT8174, the silica may be treated with  $\text{SiCl}_4$ ,  $\text{SiCl}_4$ ,  $\text{Si}(\text{OMe})_4$ ,  $\text{Si}(\text{OEt})_4$ ,  $\text{SiCl}_3\text{CH}_3$ ,  $\text{SiCl}_3\text{CH}_2\text{SiCl}_3$ ,  $\text{SiCl}_3\text{CH}_2\text{CH}_2\text{SiCl}_3$ ,  $\text{Si}(\text{OMe})_3\text{CH}_2\text{Si}(\text{OMe})_3$ ,  $\text{Si}(\text{OMe})_3\text{CH}_2\text{CH}_2\text{Si}(\text{OMe})_3$ ,  $\text{Si}(\text{OEt})_3\text{CH}_2\text{Si}(\text{OEt})_3$ , or  $\text{Si}(\text{OEt})_3\text{CH}_2\text{CH}_2\text{Si}(\text{OEt})_3$  to increase the modification by the silanizing agent.

Although coatings applied by one-step processes do not necessarily require subsequent treatments in order to create coatings with the HP/OP properties described herein, they may be subject to subsequent treatments. Such treatments may enhance, for example, one or more of the hydrophobicity, superhydrophobicity, oleophobicity or anti-icing properties, and may be made either before or after curing (e.g., by heating) the coatings applied using a one-step process.

In one embodiment, a one-step process may further comprise applying a composition comprising a silanizing agent (e.g. a compound of formula (I)). In another embodiment, a one-step process may further comprise applying a composition comprising a silicon containing reagent that can increase the number of site that can react with silanizing agents, followed by a composition containing a silanizing agent. Reagents that will increase the number of sites on silica particles and other components of coatings that can react with silanizing agents include, but are not limited to:  $\text{SiCl}_4$ ,  $\text{SiCl}_4$ ,  $\text{Si}(\text{OMe})_4$ ,  $\text{Si}(\text{OEt})_4$ ,  $\text{SiCl}_3\text{CH}_3$ ,  $\text{SiCl}_3\text{CH}_2\text{SiCl}_3$ ,  $\text{SiCl}_3\text{CH}_2\text{CH}_2\text{SiCl}_3$ ,  $\text{Si}(\text{OMe})_3\text{CH}_2\text{Si}(\text{OMe})_3$ ,  $\text{Si}(\text{OMe})_3\text{CH}_2\text{CH}_2\text{Si}(\text{OMe})_3$ ,  $\text{Si}(\text{OEt})_3\text{CH}_2\text{Si}(\text{OEt})_3$ , or  $\text{Si}(\text{OEt})_3\text{CH}_2\text{CH}_2\text{Si}(\text{OEt})_3$ . Where those reagents contain chlorine, they may react with water or moisture to convert residual Cl, bound to Si atoms that is not displaced in the reaction with the coating components, into SiOH groups, which in addition to other groups, may also subsequently react with a silanizing agent.

In another embodiment, a one-step process may further comprise applying a composition comprising one or more second particles over the coating formed in the one step process. In such embodiments, the second particles can be applied to the coating formed in the one step process in a suitable binder compatible solvent (e.g., hexane in many instances). The second particles (e.g., TS-720 or TLD-720, or TLD201) may be suspended in a suitable solvent in a concentration range (e.g., 2% to 10%; 4% to 12%; 5%–15%, or 5% to 20% w/v) for application to the coating.

In an embodiment where the coating applied to a substrate in a one-step process did not contain second particles treated so that they are hydrophobic, superhydrophobic, or oleophobic (i.e., have HP/OP properties), the one step process can further comprise applying a composition comprising either: a silanizing agent; or a composition comprising a silicon con-

taining reagent that will increase the number of sites that can react with silanizing agents, followed by a composition containing a silanizing agent.

In another embodiment, where the coating applied in a one-step process does not contain second particles treated so that they are hydrophobic, superhydrophobic, oleophobic, the one step process can further comprise applying one or more second particles treated so that they are hydrophobic, superhydrophobic, or oleophobic. In such an embodiment, the second particles may comprise one or more independently selected alkyl, haloalkyl, or perfluoroalkyl groups.

#### 6.1.1 Block Copolymers

A wide variety of block copolymers may be employed in the one and two step coating systems described herein. Where they are employed, they are typically present in a range selected from: of 1% to 15%, 1% to 3%, 1% to 5%, 6%-10% 5, or 11% to 15% by weight. The block copolymers may be one or more of hydrophobic block copolymers, diblock copolymers, triblock copolymers, tetrablock copolymers and combinations thereof.

Block copolymers may be prepared or purchased from a variety of sources. For example Kraton® D series block copolymers are available from Shell Chemical Company (Houston, Tex.), Europrene® Sol T block copolymers are available from EniChem (Houston, Tex.), Vector® block copolymers are available from Exxon (Dexco) (Houston, Tex.), and Solprene® block copolymers from Housmex® (Houston, Tex.).

#### 6.2 Two Step Coating Processes

In some embodiments, the coatings may be applied using methods where, in a first step, a binder and first particles are mixed to form a coating composition, which does not contain the second particles, prior to the application of the coating composition to the surface. Following the application of that coating composition, a second step is conducted wherein a composition comprising second particles is applied to the surface over the coating composition. For the purpose of this disclosure, such methods are termed two-step method or processes.

The second step may be conducted either before or after curing the coating composition applied in the first step. In one embodiment, the composition comprising second particles is applied after any solvents in the coating composition have evaporated, but before the composition has been cured. In another embodiment, the composition comprising second particles is applied after the coating composition has been cured.

In one embodiment, a two-step process of applying a coating to a substrate may comprise the steps:

- a) applying to said substrate a coating composition comprising (i) a binder and (ii) first particles having a size of about 30 microns to about 225 microns, to provide a substrate coating; and
- b) applying to said substrate coating a composition comprising second particles having a size of about 1 nanometer to 25 microns that optionally comprise one or more independently selected alkyl, haloalkyl or perfluoroalkyl groups covalently bound, either directly or indirectly, to said second particles.

In two-step methods the binders, first particles, second particles and silanizing agents described above may be employed. First particles may be less than 30 microns, and may be particles with an average size in the range of about 1 µm to about 225 µm as described above.

Although coatings applied by two-step processes do not necessarily need to undergo subsequent treatments in order to create coatings with the HP/OP properties described herein,

they may be subject to subsequent treatments. Such treatments may enhance, for example, one or more of the hydrophobicity, superhydrophobicity, oleophobicity or anti-icing properties, and may be made either before or after curing (e.g., by heating) the coatings applied using a two-step process.

In one embodiment, a two-step process may further comprise applying: a composition comprising either: a silanizing agent (e.g. a compound of formula (I). In another embodiment, a two-step process may further comprise applying a composition comprising a silicon-containing reagent that will increase the sites that can react with silanizing agents, followed by a composition containing a silanizing agent. Reagents that will increase the number of sites on silica particles and other components of coatings that can react with silanizing agents include, but are not limited to:  $\text{SiCl}_4$ ,  $\text{SiCl}_4$ ,  $\text{Si}(\text{OMe})_4$ ,  $\text{Si}(\text{OEt})_4$ ,  $\text{SiCl}_3\text{CH}_3$ ,  $\text{SiCl}_3\text{CH}_2\text{SiCl}_3$ ,  $\text{SiCl}_3\text{CH}_2\text{CH}_2\text{SiCl}_3$ ,  $\text{Si}(\text{OMe})_3\text{CH}_2\text{Si}(\text{OMe})_3$ ,  $\text{Si}(\text{OMe})_3\text{CH}_2\text{CH}_2\text{Si}(\text{OMe})_3$ ,  $\text{Si}(\text{OEt})_3\text{CH}_2\text{Si}(\text{OEt})_3$ , or  $\text{Si}(\text{OEt})_3\text{CH}_2\text{CH}_2\text{Si}(\text{OEt})_3$ .

Where the coating applied in a two-step process does not contain second particles treated so that they are hydrophobic, superhydrophobic, or oleophobic (i.e., have HP/OP properties), the two-step process can further comprise applying a composition comprising either a silanizing agent or a composition comprising silicon containing reagent that will increase the number of sites that can react with silanizing agents followed by a composition containing a silanizing agent.

#### 6.3 Thermal Deposition Processes.

Thermal spray processes including Plasma Spraying, Warm Spraying Wire Arc Spraying, High Velocity Oxyfuel (HOVF), Rockide® process, and Twin-Arc spraying may be employed to prepare coatings that have one or more of hydrophobic, superhydrophobic, oleophobic, or anti-icing characteristics. Thermal spray coating processes as used herein are a form of a two-step coating process in which a base coat material is applied to the substrate, alone or in combination with a second particle.

In one embodiment, a thermal deposition process for applying a coating to a substrate may comprise the steps:

- a) applying to said substrate by a thermal spray process a base coating spray composition optionally comprising first particles having a size of about 1 micron to about 100 microns, to provide a base coating; and
- b) applying to said base coating one or more of: (i) a composition comprising one or more second particles having a size of about 1 nanometer to 25 microns that optionally comprise one or more independently selected alkyl, haloalkyl or perfluoroalkyl groups covalently bound, either directly or indirectly, to said second particles; (ii) a composition comprising one or more silanizing agents, or (iii) a composition comprising a silicon-containing reagent that increases the number of sites on silica particles or other components of thermal spray coatings that can react with silanizing agents, followed by a composition comprising a silanizing agent.

Due to the high temperature, oxidizing conditions, and the composition of the base coating spray composition, the base coating will contain a variety of functionalities that may be modified to impart HP/OP characteristics to the coating. The base coat can be treated as in step (b) to produce surfaces with water contact angles measured at room temperature of about 120° to about 170°. In some embodiment the contact angle of the surface with water will be in a range selected from about 120° to about 140°, about 130° to about 150°, about 140° to about 160°, or about 150° to about 170°.

In one embodiment the thermal spray process is selected from High Velocity OxyFuel (HVOF) and Twin-Arc spray. The size of the first particles that may be applied in a base coating spray composition varies depending on the thermal spray process employed. For HVOF, first particles have a size in a range selected from: about 1 to about 75 microns, or about 5 to about 50 microns, or about 25 microns to 70 microns, or about 10 to about 40 microns. For plasma spray processes the particles are typically in the range of about 15 microns to about 45 microns, and for combustion processes, the range is from about 45 microns to about 100 microns. Thermal spraying using the Rockide® process, where particles to be sprayed are prepared in the form of ceramic rods and thermal spraying employing Twin-Arc Processes, which spray metallic materials feed in the form of a wire are less sensitive to the starting particle sizes.

In one embodiment the base coating spray composition comprises one or more metals, metal alloys, metal oxides, metalloids, metalloid oxides, carbides (e.g., SiC) or nitrides (e.g., Si<sub>3</sub>N<sub>4</sub>). In another embodiment, the base coating spray composition comprises one or more metals in combination with one or more metal oxides, metalloid oxides or carbides. In an embodiment, the base coating spray composition comprises one or more of: zirconia, Al<sub>2</sub>O<sub>3</sub>, Ni—Cr (e.g., 80%-20%), stainless steel (e.g., a 316 stainless), tungsten carbide/cobalt, chromium carbide/nickel and nickel/aluminum.

In an embodiment, one or more independently selected carbides, silicates, metal oxides or metalloid oxides can be bonded to, or impregnated into, the surface of a substrate using thermal spray processes as a base coat. In another embodiment, one or more independently selected compositions comprising: a silicate (e.g., silica); zirconia (ZrO<sub>2</sub>), alumina (Al<sub>2</sub>O<sub>3</sub>), 80%-20% Ni—Cr, 316 Stainless Steel, tungsten carbide/cobalt, chromium oxide, chromium carbide/nickel, and nickel aluminide (IC-50) and the like can be bonded to, or impregnated into, the surface of a substrate to form a base coat using thermal spray deposition. In another embodiment the base coating comprises one or more metals, metal alloys, metal oxides, metalloids, metalloid oxides, carbides or nitrides, in combination with one or more metal oxides, metalloid oxides, or one or more alloys formed by thermal spray deposition. Such base coat compositions may optionally comprise one or more second particles.

Some compositions that can be applied by thermal spray and the systems used for thermal spray application

Material	Thermal Spray System
Zirconia stabilized	Rokide gun
Al <sub>2</sub> O <sub>3</sub>	Rokide gun
80-20 Ni—Cr	Rokide gun
316 Stainless steel	HVOF
Tungsten carbide/cobalt	HVOF
Chromium carbide/nickel	HVOF
Nickel aluminide (IC-50)	HVOF

Where base coating spray compositions comprise one or more independently selected second particles, the particles need to be compatible with the thermal spray process conditions (e.g., the high temperature). In an embodiment, the second particles are comprised of one or more materials independently selected from metals, metal oxides, metalloids, oxides of a metalloid, silicates, or a glass (e.g., silica or alumina).

In an embodiment, the second particles have an average size in a range selected from: about 100 nm to about 50 microns; about 500 nm to about 50 microns; about 500 nm to

about 25 microns; about 1 micron to about 50 microns; about 1 micron to about 25 microns; about 5 microns to about 25 microns; about 5 microns to about 50 microns; about 10 microns to about 25 microns; about 10 microns to about 35 microns, or about 10 microns to about 50 microns. In a further embodiment the second particles are particles of silica or alumina.

Once bonded to the substrate, groups present on the surface (including groups on the surface of first or second particles) that are capable of binding functionalities imparting OH/OP properties (e.g., metal or metalloid oxides on the substrate's surface) can subsequently be modified by the application of reagents (e.g., silanizing agents) that alter the surface properties. In an embodiment, metal or metalloid oxides bound via the thermally bonded materials are modified with silanizing reagents bearing one or more alkyl, haloalkyl, fluoroalkyl, or perfluoroalkyl functionalities to the surface of the coating. Additionally, coatings applied by thermal spray processes may also be modified to increase their HP/OP properties by treatment with second particles bearing one or more functionalities that provide HP/OP properties (e.g., silica particles treated with a silanizing agent such as SIT8174 or polydimethylsiloxane treated fumed silica such as TS-720). It is also possible to use a combination of a silanizing agent and a second particle (e.g., fumed silica second particles untreated or treated with a silanizing agent) to treat the coatings applied by thermal spray processes.

In one embodiment, the silanizing agents are compounds of formula (I) and embodiments thereof describe above.

In another embodiment, the silanizing reagent is selected from tridecafluoro-1,1,2,2-tetrahydrooctyl)silane (SIT8173.0); (tridecafluoro-1,1,2,2-tetrahydrooctyl)trichlorosilane (SIT8174.0); (tridecafluoro-1,1,2,2-tetrahydrooctyl)triethoxysilane (SIT8175.0); (tridecafluoro-1,1,2,2-tetrahydrooctyl)trimethoxysilane (SIT8176.0); (heptadecafluoro-1,1,2,2-tetrahydrodecyl)dimethyl(dimethylamino)silane (SIH5840.5); (heptadecafluoro-1,1,2,2-tetrahydrodecyl)tris(dimethylamino)silane (SIH5841.7); n-octadecyltrimethoxysilane (SI06645.0); n-octyltriethoxysilane (SI06715.0); and nonafluorohexyldimethyl(dimethylamino)silane (SIN6597.4).

In another embodiment, the silanizing reagent may be selected from dimethyldichlorosilane, hexamethyldisilazane, octyltrimethoxysilane, polydimethylsiloxane, or tridecafluoro-1,1,2,2-tetrahydrooctyl trichlorosilane.

In another embodiment the silanizing agent comprises (tridecafluoro-1,1,2,2-tetrahydrooctyl)trichlorosilane (SIT8174.0).

In another embodiment, the second particles applied to thermal spray coated surfaces are treated with one or more agents that provide HP/OP properties. In an embodiment, the agents are selected from compositions comprising one or more silanizing agents of formula I. In other embodiments, the agents are compositions comprising one or more of tridecafluoro-1,1,2,2-tetrahydrooctyl)silane (SIT8173.0); (tridecafluoro-1,1,2,2-tetrahydrooctyl)trichlorosilane (SIT8174.0); (tridecafluoro-1,1,2,2-tetrahydrooctyl)triethoxysilane (SIT8175.0); (tridecafluoro-1,1,2,2-tetrahydrooctyl)trimethoxysilane (SIT8176.0); (heptadecafluoro-1,1,2,2-tetrahydrodecyl)dimethyl(dimethylamino)silane (SIH5840.5); (heptadecafluoro-1,1,2,2-tetrahydrodecyl)tris(dimethylamino)silane (SIH5841.7); n-octadecyltrimethoxysilane (SI06645.0); n-octyltriethoxysilane (SI06715.0); and nonafluorohexyldimethyl(dimethylamino)silane (SIN6597.4). In an embodiment, the second particles applied in step (b) are treated with hexamethyldisilazane, octyltrimethoxysilane, polydimethylsiloxane, or tridecafluoro-1,1,



2,2-tetrahydrooctyl trichlorosilane. In another embodiment, the second particles applied in step (b) are comprised of silica and treated with one or more of hexamethyldisilazane, octyltrimethoxysilane, polydimethylsiloxane, or tridecafluoro-1, 1,2,2-tetrahydrooctyl trichlorosilane. In some embodiments the silane is tridecafluoro-1,1,2,2-tetrahydrooctyl trichlorosilane which may also be used to treat second particles, such as silica particles, and any metal oxides formed in the thermal spray process.

Prior to the application of silanizing agents it is possible to modify the coatings applied by thermal spray processes using a composition comprising a silicon containing reagent that increases the number of sites on silica particles or other components of thermal spray coatings that can react with silanizing agents. In one embodiment silicon containing reagents that increases the number of sites on silica particles comprise one or more of:  $\text{SiCl}_4$ ,  $\text{SiCl}_4$ ,  $\text{Si}(\text{OMe})_4$ ,  $\text{Si}(\text{OEt})_4$ ,  $\text{SiCl}_3\text{CH}_3$ ,  $\text{SiCl}_3\text{CH}_2\text{SiCl}_3$ ,  $\text{SiCl}_3\text{CH}_2\text{CH}_2\text{SiCl}_3$ ,  $\text{Si}(\text{OMe})_3\text{CH}_2\text{Si}(\text{OMe})_3$ ,  $\text{Si}(\text{OMe})_3\text{CH}_2\text{CH}_2\text{Si}(\text{OMe})_3$ ,  $\text{Si}(\text{OEt})_3\text{CH}_2\text{Si}(\text{OEt})_3$ , or  $\text{Si}(\text{OEt})_3\text{CH}_2\text{CH}_2\text{Si}(\text{OEt})_3$ . The number of sites on silica particles or other components of thermal spray coatings that can react with silanizing agents can also be increased by other treatments including, but not limited to: etching the surfaces with acids such as HF, HCl,  $\text{H}_2\text{SO}_4$  and by electropolishing.

Following application of either or both of a silanizing agent or second particles, the coatings are cured. Curing may be accomplished at room temperature (about 18 to about 22° C.) for 24 hours; however, it may be desirable to use elevated temperatures and/or to adjust the curing time depending on the silane or second particles employed.

Thermal deposition process for applying a coating may be applied to a variety of substrates. Such substrates include, but are not limited to, metals, metalloids, ceramics, and glasses. In some embodiments the surfaces will be in the form of metal plates, metal sheets or metal ribbons.

Depending on the coating composition employed and the application process, deposits formed will have different thicknesses and widths. The material deposited by thermal spray deposition, which consist of flattened splatters or lamellae, are formed by flattening of the liquid droplets and can have a wide range of dimensions. Individual lamellae often have thickness in the range from a 1 or 2 microns to 40, 60, 80 or even 100 microns. The same lamellae may have widths that range from a 10 microns to 1,000 microns or more.

## 7.0 PERFORMANCES

The performance of coatings described herein may be measured by any of a variety of means, which are relevant to a coating's ability to perform under a variety of circumstances.

The coatings described herein provide high levels of hydrophobicity, easily reaching into the range of superhydrophobicity as assessed by the contact angle of water with the surface. In addition, the coatings also display oleophobicity, which is most pronounced when fluoroalkyl moieties (groups) are employed to introduce hydrophobicity into the coatings.

Coatings described herein have the ability to resist the loss of hydrophobicity when challenged in a mechanical abrasion test. The mechanical durability of the coatings described herein may be assessed in either manual or automated tests (e.g., Taber Abraser testing). Overall, the coatings offer high resistance to the loss of HP/OP properties in manual tests and in tests on a Taber apparatus, with two step application processes using polymeric binder systems out performing one-step processes. Two-step coatings are capable of withstand-

ing more than 5,000 cycles in manual abrasion tests, as compared to several hundred for one-step process and thermal spray processes. Polyurethane compositions with glass second particles (e.g., POLANE binders with glass spheres used as base coat, with a top coating of silica gel (silica nanotubes) treated with  $\text{SiCl}_4$  and silanized with SIT 8174.0) offer some of the highest resistance to mechanical abrasion-induced loss of HP/OP properties. Mechanical abrasion tests show that such coatings can withstand more than 700 cycles of Taber abrasion testing.

The coating compositions described herein are compatible with a wide variety of surfaces. Moreover, the diversity of the binder systems (e.g., thermal spray, polymeric binders, thermoplastic binders) offers a wide range of properties in addition to hydrophobicity that may be advantageously employed. For example, coatings such a fluoropolymers not only show high resistance to the loss of HP/OP properties in mechanical abrasion tests, but those coating compositions tend to be UV resistant due the stability of the fluoropolymers employed.

The coatings described herein are also stable to environmental conditions including low temperatures, wetting, salt resistance, ice formation and the like, indicating they can be employed, in a variety of harsh environments for purposes such as the prevention of ice formation and accumulation.

In addition to the other forms of compatibility the coating described herein are flexible, which permits coating materials such as cables (e.g., high voltage electric transmission lines), and flexible tapes that can be used in a variety of applications, including rapidly forming spill-resistant barriers on a diversity of surfaces. The coatings are resistant to separation from their substrates even upon repeated heating and cooling or on exposure to liquid nitrogen. Moreover, the coatings also display a significant ability to remain attached to surfaces even when they are bent at temperatures well below freezing (0° C.).

The combination of the durable hydrophobicity, stability under a variety of conditions including exposure to salt water solution, good surface adherence and flexibility, and the ability to reduce drag, demonstrates the suitability of the coatings for high performance coatings on boat hulls. Water droplet contact angle hysteresis measurements suggest the coatings maintain a significant air fraction associated with their surfaces when submerged, which lead to the reduction in drag. Water droplet hysteresis data, along with the air bubble observed on surfaces subject to drag measurements, typically 0.1-0.3 mm in size, suggest the use of bubbler systems to maintain the surface air associated with the coatings to obtain the maximum drag reduction by the coatings, particularly when applied to boat hulls.

## 8.0 EXEMPLARY APPLICATIONS OF HP/OP SURFACES

The HP/OP properties of the coatings described herein give rise to numerous diverse applications for the coatings, some of which are set forth in the exemplary applications recited below. Applications in addition to those set forth below will be immediately apparent, and as such, the exemplary applications of the coatings are in no way intended to be limiting on the scope of the uses envisioned for the coatings.

The HP/OP properties of the coatings, and particularly their ability to resist the formation and/or adherence of ice to surfaces, gives rise to a variety of uses including, but not limited to:

Electrical transmission wires/cables that are resistant to ice formation and/or accumulation that can increase the weight of the overhead transmission lines and cause sagging or even breakage;

Aircraft wings and air surfaces that are resistant to ice formation and/or accumulation that can restrict the movement wing components (flaps etc.) and other air surfaces, and which can reduce the need for expensive and time-consuming deicing operations;

Helicopter blades that are resistant to ice formation and/or accumulation which can reduce the need to use deicing heaters which can consume fuel and the failure of which requires refurbishing or replacing of the helicopter blades;

Valves used to Control Water Flow at Hydro Dams that are resistant to freezing in position as the result of ice formation and/or accumulation, and which minimize the need to heat valves when necessary for their operation. (e.g., with gas torches);

Road and Highway Bridges and Bypasses resistant to ice formation and/or accumulation in subfreezing conditions;

Firefighters hats and equipment that is resistant to ice formation and/or accumulation that can occur when the equipment is used in severe cold temperatures, and exposed to water; and

Ice formation and/or accumulation resistant decks, railings, masts, antennas, and other exposed surfaces of boats, ships lighthouses, and buoys, which are operated in cold weather.

The HO/OP properties of the coatings described herein, which resist the wetting of surfaces to which they are applied, can be used to reduce the friction at the water/substrate interface. The use of the coatings described herein to reduce of friction at the water/substrate interface has a variety of uses including, but not limited to:

Pumps with improved efficiency due to reduction of friction, including friction at pump impellers;

Boat, ship, and barge hulls with reduced drag due to the reduced friction between the hull and water; resulting in more efficient use of fuel;

Windmill blades with increased efficiency due to a reduction in the friction between moist air and/or the effects of rain and water accumulation on the blades surface.

The HO/OP properties of the coatings described herein, which resist the wetting of surfaces to which they are applied, can be used to reduce the corrosion of materials, particularly metals. The use of the coatings described herein in corrosion reduction has a variety of uses, including but not limited to:

Bridges resistant to corrosion from water, including salt water, e.g., from salt sprays used during the winter;

Corrosion resistant guard railings used on roads and highways, and railings used along walks and stairs, public parks, railing is both galvanized steel and tubing;

Corrosion resistant coatings for industrial equipment, particularly metals (e.g., ferrous metals) exposed the weather.

Due to the HO/OP properties of the coatings described herein, the coatings may be used to prevent water penetration into the wood, which causes swelling that can be exaggerated under subzero conditions, warping, exfoliation, which can lead to rotting. The use of the coatings described herein in corrosion reduction finds a variety of uses, including but not limited to, wood and particle board resistant to the damaging effects of water.

Other uses of the HO/OP coatings described herein include a variety of applications, that include, but are not limited to:

Glasses and ceramics that are self cleaning, where the coatings described herein may be employed, for example, as arc-resistant coatings on insulators used in electrical transmission systems where dirt or salt deposits, alone or in combination with water, can allow arcing with significant electrical energy losses;

Cement and Masonry Products and surfaces resistant to damage in freezing weather from water that has penetrated the surfaces;

Paper Products and Fabric resistant to water and moisture, including, but not limited to: paper and fabric moisture barriers used for insulation and under shingles or roofing; cardboard tubes/pipes, are used to cast concrete pillars (water penetrating the seams of the tubes can leave seams and other defects in the pillars that need to be fixed by grinding operation; water resistant paper and cardboard packing;

Composites including, but not limited to HP/OP roofing shingles resistant to (1) the loss of aggregate particles, (2) ice formation, which can damages the shingles and the supporting roof structure and (3) stains that develop on shingles over time, presumably, from wetting.

### 8.1 Spill Resistant Borders

A spill-resistant border is a portion of a surface forming a perimeter around an area of a surface that has a lower hydrophobicity and/or lower oleophobicity than the border. Spill-resistant borders can prevent water and other liquids from spreading or flowing beyond the position of a border on a planar or substantially planar surface that is placed in a substantially level horizontal position (see FIG. 1.) Such borders can prevent the spread of an aqueous liquid until it exceeds a level that is about 4.5 mm higher than the surface. In some instances the liquids can be aqueous solutions, suspensions or emulsions. In other instances, the liquids can be lipids or oils that are prevented from spreading beyond a border until the level of the oil or lipid exceeds about 2 mm above the surface on which the border is formed. In other instances the liquid can be an alcohol (e.g., methanol, ethanol, a propanol, a butanol, or a pentanol) or a liquid comprising an alcohol (e.g., water and alcohol combination including alcoholic beverages such as beer, wine and distilled liquors).

The HP/OP coatings described herein may be used to prepare spill resistant borders either by directly applying an HP/OP coating to a portion of a surface (with or without the use of a mask) or by applying a tape or ribbon to the surface where one surface of the tape or ribbon is treated with an HP/OP coating.

Where the surface, or a portion of the surface, is substantially planar, the spill-resistant border may be placed at or near the edges of the planar surface or near the edge of the portion that is substantially planar, such that the spill-resistant border surrounds a region of the surface that has a lower hydrophobicity or lower oleophobicity than the spill-resistant border. Alternatively, the border may be placed so as to form a boundary encompassing one or more portions of the surface that have a lower hydrophobicity or oleophobicity than the border. Thus, borders may, in some cases, be placed at the edges of (e.g., at or near the edges of the treated surface) or form one or more barriers separating regions of a surface that have lower hydrophobicity than the borders or bathers.

One embodiment provides surfaces comprising a hydrophobic and/or oleophobic spill-resistant border, wherein the border forms a perimeter around at least one area of the surface that has a lower hydrophobicity and/or lower oleophobicity than the border. In another embodiment, the surface may comprise a hydrophobic and/or oleophobic spill-resistant border, wherein said border forms a perimeter

around at least two, or at least three, or at least four, areas of the surface that have a lower hydrophobicity and/or lower oleophobicity than the border.

In some embodiments a border may be placed at the edge of a surface, in which case it may be referred to as an "edge." In other embodiments a border may be placed near an edge of a surface, such as in the form of a strip parallel or substantially parallel to one or more edges of a surface. In some embodiments a border may be placed on a surface at a position that is not the edge such that the border forms a perimeter around one or more areas that have a lower hydrophobicity and/or lower oleophobicity than the border.

Where a border is not placed at the edge it may be termed a "barrier." Barriers may divide a surface into several regions that have a lower hydrophobicity and/or lower oleophobicity than the border. Each area having a barrier as a perimeter will separately prevent the spreading of liquid between different areas of the surface. The regions separated by barriers may be in variety of forms. For example, the regions may be in the form of a series of concentric circles or a series of regular quadrilaterals (e.g., squares or rectangles, hexagons, or triangles). Barriers may retain liquids at the same height as a spill-resistant border placed at an edge or optionally may have a lesser ability to retain liquids than the border at the edge.

In some embodiments a border in the form of an edge, or a border located at or near the edge of the surface, may be employed with borders in the form of barriers. In such an embodiment the surface will not only prevent the spread of liquids between regions separated by barriers, but also may prevent or stop liquids from flowing off the surface by blocking passage of the liquid over the border at the edge. Where the barriers have a lesser ability to retain liquids than the border, a spill that overwhelms a barrier will spread to the next area before overflowing the edge. Some examples of spill-resistant borders, including those with edges and barriers, and combinations thereof, may be seen in FIG. 2.

Spill-resistant borders (including borders in the form of edges and barriers), regardless of the pattern in which they are formed, are substantially 2-dimensional structures. The width of the HP/OP regions of a surface forming spill-resistant borders can vary depending on the specific application in which the borders are intended to be used. In some embodiments, the borders may be from about 0.2 to about 2 inches in width, or alternatively, about 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.25, 1.3, 1.4, 1.5, 1.75 or 2.0 inches (about 5 mm to 50 mm) in width. In one embodiment, where the borders are intended for use on food preparation or storage surfaces, (e.g., cutting boards, glass shelving for refrigerators, or countertops) the borders in the range of 0.2 to 2.0 inches. In other embodiments, such as where the spill-resistant borders are intended for use on food preparation or storage surfaces, the borders can be about 0.4 to 1 inch wide, or alternatively, about, 0.4, 0.5, 0.6, 0.7, 0.75, 0.8, 0.9, or 1.0 inches wide. Border width does not have to be uniform, and where borders on a surface comprise an edge and barriers, the edge and barriers may be of different widths or even varying widths on the same surface.

Where a combination of a border, such as a border in the form of an edge, and a barrier are used, the hydrophobicity of the barrier and edge may be controlled such that liquids will be prevented from spreading between different areas of the surface, but the highest resistance to liquid spreading (the highest height of liquid retained) will be at the edge. Thus, in the case of a spill that overflows an area surrounded by a barrier, the spill would flow to an adjacent area, rather than over the edge.

Spill-resistant borders and barriers may be used to direct liquid toward one or more drains in a surface and can be arranged to channel spilled liquids toward a drain (see e.g., FIG. 2 panels D and E). Borders in the forms of edges and/or barriers may be also combined with drains in a surface so as to direct liquids to a drain or collection site/container. Drains may be in the form of an opening, depression or trough (e.g., slot, hole, or groove) in the surface bearing the border. Openings, depressions, or troughs may be connected to tubing or pipes that will permit liquid to be collected or channeled to a desired location (e.g., a collection container or sewer waste line). Barrier lines that form incomplete perimeters around areas of a surface may also be used to channel liquids towards a drain (see FIG. 2, Panel D); particularly where the barrier lines form a complete perimeter except at the point where they end at or near a drain (see FIG. 2, Panel E). In one embodiment, one or more drains may be placed at the edge of surface so that the border forms a continuous perimeter around an area of the surface up to the point where the drain is located, with the drain completing the perimeter formed by the border.

In an embodiment, a spill resistant border can be formed on a surface that has a contact angle with water at room temperature that is less than about 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, or 120 degrees, and where the border has a contact angle with water at room temperature that is greater than the contact angle of water with the surface on which it is formed by about 7, 8, 9, 10, 20, 30, 40, 50, or 60 degrees measured at room temperature (about 68°-72° F.).

Spill-resistant borders, may be employed for a variety of purposes, including, but not limited to, glass shelving for refrigerators, or countertops, laboratory work benches, or cutting boards.

The tapes and ribbons (and sheet) described above may be made from a variety of materials including, but not limited to, metal (e.g., aluminum), plastic, paper, fiber glass and the like. Such tapes and ribbons may be employed for variety of other purposes than preparing spill resistant borders, including but not limited to, their use as anti-icing tapes, and to provide corrosion resistance.

#### Example 1

##### Superhydrophobic and Oleophobic Surface Coatings Formed with Three Binder Systems Without Added First Particles

Three 4-inch×4-inch aluminum plates (0.062-in. thick) are cleaned with acetone. Each plate is spray-coated with a base coat (2 ml) of one of the following binders: Self-Etching Primer (a lacquer based primer from Eastwood Co., Pottstown, Pa.); POLANE® B (a polyurethane based binder from Sherwin Williams, Harrisburg, Pa.) or LUMIFLON® (a solvent soluble fluoropolymer from Asahi Glass Co., Exton, Pa.).

Following application of the binder base coat, and before the base coat dries, each of the plates was top-coated with CAB-O-SIL TS-720 (Cabot Corp., Billerica, Mass.) fumed silica second particles (e.g., second particles) having a nominal BET surface area of 200 m<sup>2</sup>/g treated with polydimethylsiloxane. The plate coated with Self-Etching Primer was top coated with 2 ml of a TS-720 suspension (4.2 g TS-720 per 100 ml of ethanol). Plates coated with POLANE® B or LUMIFLON® are top coated with 2 ml of TS-720 suspension (4 g per 100 ml of hexane). Plates coated with Self-Etching

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Primer are cured for 30 min, at 200° F., and plates coated with the other two binders are cured for 1.5 h at 200° F. in an electric oven.

Coatings are assessed for their hydrophobicity (contact angel with water), submerged water durability, mechanical durability and chemical durability.

The hydrophobicity of the coatings is assessed by measuring the contact angle of water with the coating. Measurements are made using a T200 Theta Optical Tensiometer on newly prepared coatings and after durability testing using a Taber unit (see below).

Mechanical durability can be assessed by a variety of methods, including manual abrasion with preset weights or on commercial apparatus such as those available from Taber Industries (North Tonawanda, N.Y.).

For the purpose of this disclosure manual abrasion testing (hand rub method) is conducted using a cylindrical 800-g weight with a flat bottom (about 1.75 pounds) having a base diameter of about 4.45 cm (1.75 inches) covered with a 50:50 cotton/polyester fabric. Testing is conducted by moving the weight with a reciprocating motion (1 rub or abrasion cycle is equivalent to 1 pass of the weight across the surface). The roll-off angle for water is checked at incline angles of 3°, 6°, and/or 9° by placing 20 water droplets on the portion of the surface (e.g., the portion subjected to manual abrasion testing). The end of life of the coating determined by manual abrasion testing is considered the point when most (more than 10) of the 20 droplets do not roll off the surface at the indicated degree of incline.

Abrasion testing is also conducted using a Taber Rotary Platform Abraser (Abrader), which employs two “wheels” to abrade a surface under 250-gm loads or 500-gm loads on each wheel. Each cycle counted by the instrument is equivalent to two rubs, one each from each of the wheels. The end of life for coatings subjected to Taber testing is measured using run-off angle as described for manual abrasion.

Results for the analysis of three different coatings are summarized in Table 1. In addition to the measurements describe above, plates are also assessed for their loss of coatings by directly measuring their change in weight following assessment.

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Data from the analysis of the three coatings indicates that as prepared each coating has superhydrophobic properties (the water contact angle exceeds 150°). The lacquer based Self-Etching Primer as a binder produced slight more durable coatings than either the polyurethane or fluoropolymer binder in manual abrasion testing at 3, 6 and 9° inclines. In contrast, abrasion analysis using the Taber instrument indicates that fluoropolymer binders give slightly more durable coatings

### Example 2

#### Superhydrophobic and Oleophobic Surface Coatings Prepared with First Particles

Aluminum plates (4-inch×4-inch 0.062-in.thick) are cleaned with acetone and are coated in a two step process comprising applying a base coat followed by application of a top-coat (second coat). Each plate is spray-coated with a base coat (2 ml) of one Self-Etching Primer (SEP) (Eastwood Co., Pottstown, Pa.) containing the indicated amount of the first particles listed below. After drying in air, this base coat is top-coated with 2 ml of TS-720 treated with polydimethylsiloxane suspended in ethanol (4.2 g/100 ml). After drying in air, the coated plates are dried in air and cured at 200° F. for 30 minutes (“min”) in an electric oven. Manual abrasion testing is conducted as described in Example 1. Data from the plates is shown in Tables 2a-2f.

### Example 2A

#### Coatings Prepared with Filler 512

The filler 512 black, (Xiom Corp., West Babylon, N.Y.) a thermoplastic powder is added to SEP at 0% to 40% weight to volume. The mixture was sprayed on as the base coat and top coated with TS-720 treated with polydimethylsiloxane as described above. Manual abrasion data is shown in Table 2a.

TABLE 1

Durability of Superhydrophobic Composite Coatings Formed With Three Different Binder Systems And Second Particles of TS-720.

Coating Detail			Contact Angle						
			Sprayed Amount	Degrees	After Durability Testing for	Durability Date <sup>a</sup>			Weight Change <sup>b</sup>
						Rub Cycles (800-gm Rub, 250-g Taber)	Roll-off Angle (°)		
Substrate	Binder	Top Coat	base/top (ml)	New	9' Roll-off	3	6	9	(mg)
Aluminum (4 × 4 in.)	Etch coat	4.2 g T-720 in 100 ml ethanol:	2/10	155	131	100/40	140/40	160/40	160.4
Aluminum (4 × 4 in.)	Polane ® B	4.0 g T-720 in 100 ml hexane	2/10	159	144	80/35	100/35	120/35	7
Aluminum (4 × 4 in.)	Lumiflon ®	4.0 g T-720 in 100 ml hexane	2/10	159	122	60/55	100/55	120/55	116.2

<sup>b</sup>After Taber testing with 250 g load using 9° roll-off to determine end of life.

TABLE 2a

Addition of 512 Black Thermoplastic Filler in Self-Etch Primer (SEP) Binder Coat							
Coating Detail			Two-Step Process		Cure		
Samples	Binder	Filler	Filler (g)/ 100 ml SEP	Top Coat g/100 ml	Temperature (° F.) 30 min	Number of Rubs	
						Actual	Average
Al (4 × 4 in.)	SEP	512 Black	0	4.2 TS-720	200		75
Al (4 × 4 in.)	SEP	512 Black	20	4.2 TS-720	200	200	220
Al (4 × 4 in.)	SEP	512 Black	20	4.2 TS-720	200	240	
Al (4 × 4 in.)	SEP	512 Black	25	4.2 TS-720	200	200	212
Al (4 × 4 in.)	SEP	512 Black	25	4.2 TS-720	200	225	
Al (4 × 4 in.)	SEP	512 Black	30	4.2 TS-720	200	275	317
Al (4 × 4 in.)	SEP	512 Black	30	4.2 TS-720	200	360	
Al (4 × 4 in.)	SEP	512 Black	35	4.2 TS-720	200	150	125
Al (4 × 4 in.)	SEP	512 Black	35	4.2 TS-720	200	100	
Al (4 × 4 in.)	SEP	512 Black	40	4.2 TS-720	200	200	175
Al (4 × 4 in.)	SEP	512 Black	40	4.2 TS-720	200	150	

## Example 2B

## Coatings Prepared with Filler Nulok 390

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The filler Nulok 390 (Kamin LLC, Macon, Ga.) is added to SEP at 0% to 40% weight to volume. The mixture was sprayed on as the base coat and top coated with TS-720 treated with polydimethylsiloxane as described above. Manual abrasion data is shown in Table 2b. The maximum abrasion cycles tolerated with a 17% addition of Nulok 390 were about four times the number of cycle achieved in the absence of that filler.

TABLE 2b

Addition of Nulok 390 Thermoplastic Filler in Self-Etch Primer (SEP) Binder Coat							
Coating Detail			Two-Step Process		Cure		
Samples	Binder	Filler	Filler (g)/ 100 ml SEP	Top Coat g/100 ml	Temperature (° F.) 30 min	Number of Rubs	
						Actual	Average
Al (4 × 4 in.)	SEP	Nulok 390	0	4.2 TS-720	200		75
Al (4 × 4 in.)	SEP	Nulok 390	4.6	4.2 TS-720	200	130	145
Al (4 × 4 in.)	SEP	Nulok 390	4.6	4.2 TS-720	200	160	
Al (4 × 4 in.)	SEP	Nulok 390	17	4.2 TS-720	200	275	275
Al (4 × 4 in.)	SEP	Nulok 390	25	4.2 TS-720	200	275	250
Al (4 × 4 in.)	SEP	Nulok 390	30	4.2 TS-720	200	220	230
Al (4 × 4 in.)	SEP	Nulok 390	30	4.2 TS-720	200	240	
Al (4 × 4 in.)	SEP	Nulok 390	35	4.2 TS-720	200	220	230
Al (4 × 4 in.)	SEP	Nulok 390	35	4.2 TS-720	200	240	
Al (4 × 4 in.)	SEP	Nulok 390	40	4.2 TS-720	200	240	250
Al (4 × 4 in.)	SEP	Nulok 390	40	4.2 TS-720	200	160	

## Example 2C

## Coatings Prepared with Filler XT-Series

First particles in the XT family (XT-600, XT-700, XT-750, and XT-765) (Xiom Corp, West Babylon, N.Y.) are added at

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30% or 35% weight to volume. The mixture was sprayed on as the base coat and top coated with TS-720 as described above. Manual abrasion data is shown in Table 2c. The maximum number of abrasion cycles tolerated with additions of XT first particles to SEP are about five times that achieved without any filler addition.

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TABLE 2c

Addition of XT-Series Thermoplastic as a Filler in Self-Etch Primer (SEP) Binder Coat								
Coating Detail			Two-Step Process		Cure			
Samples	Binder	Filler	Filler Type	Filler (g)/ 100 ml SEP	Top Coat g/100 ml	Temperature (° F.) 30 min	Number of Rubs	
Al (4 × 4 in.)	SEP	XT-Series	—	0	4.2 TS-720	200	75	
Al (4 × 4 in.)	SEP	XT-600	TS	30	4.2 TS-720	200	100	100
Al (4 × 4 in.)	SEP	XT-600	TS	30	4.2 TS-720	200	100	
Al (4 × 4 in.)	SEP	XT-700	Epoxy	30	4.2 TS-720	200	360	340
Al (4 × 4 in.)	SEP	XT-700	Epoxy	30	4.2 TS-720	200	320	
Al (4 × 4 in.)	SEP	XT-700	Epoxy	35	4.2 TS-720	200	340	300
Al (4 × 4 in.)	SEP	XT-700	Epoxy	35	4.2 TS-720	200	260	
Al (4 × 4 in.)	SEP	XT-750	Bond Coat	30	4.2 TS-720	200	200	220
Al (4 × 4 in.)	SEP	XT-750	Bond Coat	30	4.2 TS-720	200	200	
Al (4 × 4 in.)	SEP	XT-750	Bond Coat	30	4.2 TS-720	200	260	
Al (4 × 4 in.)	SEP	XT-750	Bond Coat	30	4.2 TS-720	200	220	
Al (4 × 4 in.)	SEP	XT-765	Zn-Epoxy	30	4.2 TS-720	200	240	240
Al (4 × 4 in.)	SEP	XT-765	Bond Coat	30	4.2 TS-720	200	240	

## Example 2D

## Coatings Prepared with Filler 200 White

The filler 200 White, (Xiom Corp, West Babylon, N.Y.), a thermoplastic bond coat powder of 10-100 microns mean diameter, is added to SEP as a filler at 15% or 30% weight to

25 volume. The mixture was sprayed on as the base coat and top coated with TS-720 treated with polydimethylsiloxane as described above. Manual abrasion data is shown in Table 2d. The maximum number of abrasion cycles tolerated with additions of 200 White filler to SEP is about four times that achieved without any filler addition.

TABLE 2d

Addition of 200 White Thermoplastic Filler in Self-Etch Primer (SEP) Binder Coat								
Coating Detail			Two-Step Process		Cure			
Samples	Binder	Filler	Filler (g)/ 100 ml SEP	Top Coat g/100 ml	Temperature (° F.) 30 min	Number of Rubs		
Al (4 × 4 in.)	SEP	200 White	0	4.2 TS-720	200	75		
Al (4 × 4 in.)	SEP	200 White	15	4.2 TS-720	200	260	280	
Al (4 × 4 in.)	SEP	200 White	15	4.2 TS-720	200	300		
Al (4 × 4 in.)	SEP	200 White	30	4.2 TS-720	200	220	230	
Al (4 × 4 in.)	SEP	200 White	30	4.2 TS-720	200	240		

50 It can be stated from the thermoplastic filler study that all of them resulted in a positive effect and improvement varied somewhat, which is obviously dependent on filler size and to some extent on filler chemistry.

## Example 2E

## Coatings Prepared with Wood Particles as First Particles

60 Wood powder of the indicated size is added to SEP at 10% or 15% weight to volume. The mixture is sprayed on as the base coat and top coated with TS-720 treated with polydimethylsiloxane as described above. Manual abrasion data is shown in Table 2e. The maximum abrasion cycles tolerated by coatings with 15% of 53 micron wood dust is over 4 times  
65 that of the coating in the absence of filler.

TABLE 2e

Addition of Wood-Dust Thermoplastic Filler in Self-Etch Primer (SEP) Binder Coat							
Coating Detail			Two-Step Process		Cure		
Samples	Binder	Filler	Filler (g)/	Top Coat	Temperature	Number of Rubs	
			100 ml SEP	g/100 ml	(° F.) 30 min	Actual	Average
Al (4 × 4 in.)	SEP	Wood Dust	0	4.2 TS-720	200		75
Al (4 × 4 in.)	SEP	53-μm Wood Dust	15	4.2 TS-720	200	320	
Al (4 × 4 in.)	SEP	53-μm Wood Dust	10	4.2 TS-720	200	320	
Al (4 × 4 in.)	SEP	43-μm Wood Dust	10	4.2 TS-720	200	270	

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## Example 2F

## Coatings Prepared with Metal Powder First Particles

Aluminum powder of the indicated size (100 or 325 mesh) or (149 or 44 microns respectively) is added to SEP at 30% or 40% weight to volume. The mixture is applied as the base coat

by spraying and top coated with TS-720 treated with polydimethylsiloxane as described above. Manual abrasion data is shown in Table 2f. The maximum abrasion cycles tolerated by coatings with the addition of 100 mesh aluminum filler is over three times that number of abrasion cycles tolerated by the coatings in the absence of any filler.

TABLE 2f

Addition of Aluminum Metal Powders Thermoplastic Filler in Self-Etch Primer (SEP) Binder Coat							
Coating Detail			Two-Step Process		Cure		
Samples	Binder	Filler	Filler (g)/	Top Coat	Temperature	Number of Rubs	
			100 ml SEP	g/100 ml	(° F.) 30 min	Actual	Average
Al (4 × 4 in.)	SEP	Al-Metal Powder	0	4.2 TS-720	200		75
Al (4 × 4 in.)	SEP	Al-101 (~100 mesh)	40	4.2 TS-720	200	280	250
Al (4 × 4 in.)	SEP	Al-101 (~100 mesh)	40	4.2 TS-720	200	220	
Al (4 × 4 in.)	SEP	Al-101 (~100 mesh)	50	4.2 TS-720	200	200	200
Al (4 × 4 in.)	SEP	Al-101 (~100 mesh)	50	4.2 TS-720	200	200	
Al (4 × 4 in.)	SEP	Al-101 (~325 mesh)	40	4.2 TS-720	200	220	220
Al (4 × 4 in.)	SEP	Al-101 (~325 mesh)	40	4.2 TS-720	200	220	
Al (4 × 4 in.)	SEP	Al-101 (~325 mesh)	50	4.2 TS-720	200	230	230

## Example 2G

## Coatings Prepared with Metal and/or Metalloid Oxide Powder First Particles

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MULLITE, which is a spinal oxide of Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> (powder ~325 mesh or 44 microns mean diameter,) is added to SEP at 10% to 40% weight to volume. The mixture is sprayed on as the base coat and top coated with TS-720 treated with polydimethylsiloxane as described above. Manual abrasion data is shown in Table 2g. The maximum abrasion cycles tolerated by coatings with the addition of MULLITE is about three and a half times the number of abrasion cycles tolerated by the coatings in the absence of any filler.

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TABLE 2g

Addition of Mullite Thermoplastic Filler in Self-Etch Primer (SEP) Binder Coat							
Coating Detail			Two-Step Process		Cure		
Samples	Binder	Filler	Filler (g)/	Top Coat	Temperature	Number of Rubs	
			100 ml SEP	g/100 ml	(° F.) 30 min	Actual	Average
Al (4 × 4 in.)	SEP	Mullite	0	4.2 TS-720	200		75
Al (4 × 4 in.)	SEP	Mullite	10	4.2 TS-720	200	100	100

TABLE 2g-continued

Addition of Mullite Thermoplastic Filler in Self-Etch Primer (SEP) Binder Coat							
Coating Detail			Two-Step Process		Cure		
Samples	Binder	Filler	Filler (g)/	Top Coat	Temperature	Number of Rubs	
			100 ml SEP	g/100 ml	(° F.) 30 min	Actual	Average
Al (4 × 4 in.)	SEP	Mullite	10	4.2 TS-720	200	100	
Al (4 × 4 in.)	SEP	Mullite	20	4.2 TS-720	200	200	175
Al (4 × 4 in.)	SEP	Mullite	20	4.2 TS-720	200	150	
Al (4 × 4 in.)	SEP	Mullite	30	4.2 TS-720	200	220	210
Al (4 × 4 in.)	SEP	Mullite	30	4.2 TS-720	200	200	
Al (4 × 4 in.)	SEP	Mullite	40	4.2 TS-720	200	260	260
Al (4 × 4 in.)	SEP	Mullite	40	4.2 TS-720	200	260	

## Example 3

## Performance of a Thermoplastic Filler in a Lacquer Based Binder

Aluminum plates (4-inch×4-inch×0.062-in.thick) are cleaned with acetone are coated in a two step process comprising applying a base coat (2 ml) of Self-Etching Primer (SEP, Eastwood Co., Pottstown, Pa.) containing 30% weight to volume of Filler 512 White (the counter part of the 512 black filler used in Example 2). After drying in air, this base

coat is top-coated with (2, 3, 4, 5 or 6 ml) of TS-720 treated with polydimethylsiloxane suspended in ethanol (4.2 g/100 ml) or suspended in hexane at 4.2 g/100 ml. After drying in air, the coated plates are dried in air and cured at 200° F. for 30 min in an electric oven. Manual abrasion testing is conducted as described in Example 1. Data from the plates is shown in Table 3.

This table clearly demonstrates that with 30% 512 filler, the rub resistance can be increased to over 500 rubs with the top layer consisting of 5 ml/plate. Ethanol and hexane are equally effective in preparing the top coat of TS-720.

TABLE 12

512 White Filler with Top Coat Varied from 2-6 ml/Plate							
Coating Details						Number	
Samples	Binder	Filler	Two-Step Process		ml/Plate	of Rubs <sup>a</sup>	
			Filler (g)/	Top Coat		Actual	Average
			100 ml SEP	g/100 ml			
Al (4 × 4 in.)	SEP	512 White	0	4.2 EtOH	2		75
Al (4 × 4 in.)	SEP	512 White	30	4.2 EtOH	2	150	175
Al (4 × 4 in.)	SEP	512 White	30	4.2 EtOH	2	200	
Al (4 × 4 in.)	SEP	512 White	30	4.2 EtOH	3	320	350
Al (4 × 4 in.)	SEP	512 White	30	4.2 EtOH	3	380	
Al (4 × 4 in.)	SEP	512 White	30	4.2 EtOH	4	420	390
Al (4 × 4 in.)	SEP	512 White	30	4.2 EtOH	4	360	
Al (4 × 4 in.)	SEP	512 White	30	4.2 EtOH	5	560	560
Al (4 × 4 in.)	SEP	512 White	30	4.2 EtOH	6	540	540
Al (4 × 4 in.)	SEP	512 White	30	4.2 Hexane	2	260	260
Al (4 × 4 in.)	SEP	512 White	30	4.2 Hexane	2	260	
Al (4 × 4 in.)	SEP	512 White	30	4.2 Hexane	3	420	400
Al (4 × 4 in.)	SEP	512 White	30	4.2 Hexane	3	380	
Al (4 × 4 in.)	SEP	512 White	30	4.2 Hexane	4	400	410
Al (4 × 4 in.)	SEP	512 White	30	4.2 Hexane	4	420	
Al (4 × 4 in.)	SEP	512 White	30	4.2 Hexane	5	520	512
Al (4 × 4 in.)	SEP	512 White	30	4.2 Hexane	5	500	
Al (4 × 4 in.)	SEP	512 White	30	4.2 Hexane	6	420	470
Al (4 × 4 in.)	SEP	512 White	30	4.2 Hexane	6	520	

<sup>a</sup>All plates were cured at 200° F. for 30 min.



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The data table demonstrates that with 30% 512 filler, it is possible to reach 500 abrasion cycles in the manual test with a top coat of 5 ml/plate of TS-720 treated with polydimethylsiloxane (about 2 mg of polydimethylsiloxane treated TS-720 per cm<sup>2</sup> of surface).

## Example 4

## Durability Performance of First Particles in Polyurethane-Based Binders

TriPLICATE aluminum plates (4-inch×4-inch×0.062-in.-thick) are cleaned and coated in a two step process comprising applying a base coat (2 ml) of POLANE® containing 20% weight to volume of: S60 glass bubbles (3M™, St. Paul, Minn.); Filler 512 Black (Xiom Corp, West Babylon, N.Y.), or Corvel Black (Rohm & Haas, Philadelphia, Pa.). After drying in air, this base coat is top-coated with 5 ml of polydimethylsiloxane treated TS-720 suspended in hexane at 4.2 g/100 ml. After drying in air, the coated plates are dried in air and cured at 200° F. for 90 min in an electric oven. Manual abrasion testing is conducted as described in Example 1. Data from the plates is shown in Table 4.

TABLE 4

First Particles in POLANE® B Binder							
Coating Details					Cure		
Samples	Binder	Filler	Two-Step Process		Temperature (° F.)	Number	
			Filler (g)/ 100 ml SEP	Top Coat g/100 ml		of Rubs	
					90 min	Actual	Average
Al (4 × 4 in.)	Polane® B	Filler	0	4.2 Hexane	200		120
Al (4 × 4 in.)	Polane® B	512 Black	20	4.2 Hexane	200	400	370
Al (4 × 4 in.)	Polane® B	512 Black	20	4.2 Hexane	200	350	
Al (4 × 4 in.)	Polane® B	512 Black	20	4.2 Hexane	200	350	
Al (4 × 4 in.)	Polane® B	560 Glass Beads	20	4.2 Hexane	200	400	370
Al (4 × 4 in.)	Polane® B	560 Glass Beads	20	4.2 Hexane	200	350	
Al (4 × 4 in.)	Polane® B	560 Glass Beads	20	4.2 Hexane	200	350	
Al (4 × 4 in.)	Polane® B	Corvel Black	20	4.2 Hexane	200	650	770
Al (4 × 4 in.)	Polane® B	Corvel Black	20	4.2 Hexane	200	850	
Al (4 × 4 in.)	Polane® B	Corvel Black	20	4.2 Hexane	200	800	

1. In all cases first particles added to polyurethane binders increased the durability of the superhydrophobic/oleophobic coatings by about three to seven fold.

## Example 5

## Durability of Coatings Prepared with Second Particle-Silicate Materials Top Coats with and without Additional Top Coat Treatments

Aluminum plates (4-inch×4-inch×0.062-in.-thick) are cleaned and a base coat (5 ml) of POLANE® B containing 20% weight to volume of Filler 512 Black (Xiom Corp, West Babylon, N.Y.) is applied to each plate in preparation for top coating. Top coatings of a second particle selected from (1) polydimethylsiloxane treated TS-720, (2) untreated M-5 fumed silica, or (3) hexamethyldisiloxane treated Nanogel

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TLD201 (Cabot Corp, Billerica, Mass.) are applied immediately after the base coating (e.g., after the bulk of solvent had evaporated).

Top coats of polydimethylsiloxane treated TS-720 (5 ml of 4.2% w/v) are applied in ethanol.

Top coats of M5 are applied by spraying 10-15 ml a 1.5% M-5 (w/v) suspension in hexane.

Top coats of Nanogel TLD201 are applied by spraying 10-15 ml of a 1.5% or 2% TLD201 suspension in hexane as indicated in the data.

In all cases, the plates were cured at 200° F. for 90 min in an electric oven. For the top coat of TS-720 the plates are ready for testing after a 90-min curing. Plates treated with For M-5 coated plates, are treated by one of two methods (method (A) or (B)) to produce superhydrophobic behavior.

Method A—a 1% solution of (tridecafluoro-1,1,2,2-tetrahydrooctyl)trichlorosilane ("SIT8174" from Gelest, Pottstown, Pa.) in hexane is applied as a top coat in the amount indicated in Table 5b. Plates treated with SIT8174 are given a second and final cure at 200° F. for 30-60 min in an electric oven.

Method B—3.5 ml of a 3-5% solution of SiCl<sub>4</sub> in hexane is applied to plates that are exposed to atmospheric moisture. Water in the atmosphere is sufficient to convert at least some Si—Cl groups into Si—OH groups, thereby increasing the number of Si—OH sites on M-5 second particles, prior to treatment with SIT8174. After treatment with SiCl<sub>4</sub>, SIT8174 is applied and the coating cured as in Method A.

In some instances Nanogel TLD201 treated plates are also treated with SIT8174 or SiCl<sub>4</sub>+SIT8174 using Method (A) or Method (B) as described above for M-5 coated plates and the amounts of the Nanogel and SIT8174 indicated in Table 5.

Data for manual abrasion testing of plates bearing the coatings from each treatment is given in Table 5 along with a control comparison. The rub data on all of the samples discussed above are summarized in Table 15.

TABLE 5b

Effect of Top Coat Chemistry with POLANE ® B Binder on Superhydrophobic Coating Durability and Oleophobic Effect													
Coating Details													
Samples	Binder	Filler	Two-Step Process		Top Coat ml/Plate	Cure				Cure			
			Filler (g)/ 100 ml Polane ® B	Top Coat g/100 ml		Time at 200° F. (min)	Inorganic Treatment of SiCl <sub>4</sub>	Silination Treatment of SIT8174	Time at 200° F. (min)	Number of rubs	Contact Angle	Oleo- phobic	
Al (4 × 4 in.)	Polane ® B	512 Black	20	4.2 T-720 EtOH	2	90 min				370		No	
Al (4 × 4 in.)	Polane ® B	512 Black	20	1.5 g M-5 Hexane	10-15	90 min	—	— 1% in Hexane	3-5	30-60	800-1000	160	Yes
Al (4 × 4 in.)	Polane ® B	512 Black	20	1.5 g M-5 Hexane	10-15	90 min	5% in Hexane	3-5 1% in Hexane	3-5	30-60	1800-2000	164	Yes
Al (4 × 4 in.)	Polane ® B	512 Black	20	1.5 g Nanogel Hexane	10-15	90 min	—	— 1% in Hexane	3-5	30-60	1000	165	No
Al (4 × 4 in.)	Polane ® B	512 Black	20	1.5 g Nanogel Hexane	10-15	90 min	5% in Hexane	3-5 1% in Hexane	3-5	30-60	2000	163	No
Al (4 × 4 in.)	Polane ® B	512 Black	20	2.0 g Nanogel Hexane	10-15	90 min.	5% in Hexane	3-5 1% in Hexane	3-5	30-60	5100	168	No

## Example 6

## Filler and Top Coat Study

Aluminum plates (4-inch×4-inch×0.062-in.thick) are cleaned and a base coat (3-5 ml) of POLANE® B containing 20% weight to volume of the indicted filler. Top coatings of second particles of polydimethylsiloxane treated TS-720 or

untreated M-5 fumed silica (Cabot Corp, Billerica, Mass.) are applied after the base coating in the indicted solvents. Plates were dried and cured at 200° F. Where indicted, coatings were treated with Gelest silane SIT8174 or SiCl<sub>4</sub> followed by treatment with SIT8174 using methods A or B described in Example 5. Table 6a sows the data with S60 filler (3M™, St. Paul, Minn.) and Table 6b for Corvel Black.

TABLE 6a

Effect of Top Coat Chemistry with POLANE ® B Binder and S60 Glass Spheres on Superhydrophobic Coating Durability and Oleophobic Effect														
Coating Details							Inorganic Treatment		Silination Treatment					
					Two-Step Process		Top	Cure	of SiCl <sub>4</sub>		of SIT8174		Cure	
			Filler (g) 100 ml	Top Coat g/ 100 ml	Coat (ml/ Plate)	Time at 200° F. (min)	Solution Concen- tration	Amount (ml/ plate)	Solution Concen- tration	Amount (ml/ plate)	Time at 200° F. (min)	Number of rubs	Contact Angle	Oleo- phobic
Samples	Binder	Filler	Polane ® B											
Al (4 × 4 in.)	Polane ® B	540 Glass	20	M-5 1.5	15	90	—			3-5	30-60	600-800	166	Yes
Al (4 × 4 in.)	Polane ® B	540 Glass	20	M-5 1.5	15	90	5% in Hexane	3-5	1% in Hexane	3-5	30-60	1200-1500	166	Yes

TABLE 6b

Effect of Top Coat Chemistry with POLANE ® B Binder and Corvel Black as Filler on Superhydrophobic Coating Durability and Oleophobic Effect														
Coating Details					Cure		Inorganic Treatment		Silination Treatment					
Samples	Binder	Filler	Two-Step Process		Top	Time	of SiCl <sub>4</sub>		of SIT8174		Cure	Number of rubs	Contact Angle	Oleo-phobic
			Filler (g)	Top	Coat	at	Solution	Amount	Solution	Amount	Time at			
			100 ml	Coat g/	(ml/	200° F.	Concen-	(ml/	Concen-	(ml/	200° F.			
			Polane ® B	100 ml	Plate)	(min)	tration	plate)	tration	plate)	(min)			
Al (4 × 4 in.)	Polane ® B	Corvel Black	20	5TS-720 Hexane	5	90	—	—	—	—5	—	800		No

TABLE 6b-continued

Effect of Top Coat Chemistry with POLANE® B Binder and Corvel Black as Filler on Superhydrophobic Coating Durability and Oleophobic Effect														
Coating Details					Cure		Inorganic Treatment	Silination Treatment						
Two-Step Process					Top	Time	of SiCl <sub>4</sub>	of SIT8174	Cure					
Samples	Binder	Filler	Filler (g) 100 ml Polane® B	Top Coat g/ 100 ml	Coat (ml/ Plate)	at 200° F. (min)	Solution (ml/ Concen- tration)	Amount (ml/ Concen- tration)	Solution (ml/ Concen- tration)	Amount (ml/ Concen- tration)	Time at 200° F. (min)	Number of rubs	Contact Angle	Oleo- phobic
Al (4 × 4 in.)	Polane® B	Corvel Black	20	M-5 1.5	15	90	5% in Hexane	3-5	1% in Hexane	3-5	60.60	3700	163	Yes

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Plates coated with SIT8174 are both superhydrophobic and oleophobic, and perform show increased durability when pre-treated with SiCl<sub>4</sub>.

## Example 8

## Optimization of M5 Top Coat

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## Example 7

## Example 8A

Superhydrophobic and Oleophobic Coating  
Resistance to Boiling Water Exposure

Two 4 inch×4 inch aluminum plates with coatings having superhydrophobic and oleophobic behavior are prepared by the procedures in Examples 5 and 6.

Plate #1: Base Coat of 20% Filler 512 in POLANE® B and top coat of M-5 silica treated with SiCl<sub>4</sub> followed by treatment with SIT8174

Plate #2: Base Coat of 20% S60 Glass beads (spheres) in POLANE® B and a top coat with M-5 silica treated with SiCl<sub>4</sub> followed by treatment with SIT8174

After curing, both plates are checked for superhydrophobic performance and then placed in a boiling water bath. The water contact angle of the coatings is checked at periodically after removing the plates from the bath and cooling to room temperature. The plates are returned to the boiling water bath after each measurement. After hours in boiling water both plates are found to show superhydrophobic performance. A final measurement on the plates shows that they also show oleophobic behavior as well.

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Aluminum plates measuring 4 Inches by 4 inches are coated with POLANE® B containing 20% 512 Black as filler. These plates are top-coated with untreated fumed M5 silica (Cabot Corp., Billerica, Mass.) suspended in hexane at 0.5, 1.0, 1.5, or 2% weight/volume. At higher percentages of M5 dispersed in hexane it becomes difficult to spray the mixture. The amount of each M5 suspension applied as top coat was also monitored by the volume applied to plate (ml/plate). The amounts applied are varied in increments of 5 ml/plate from 5 to 20 ml/plate. After the top coat is applied, the plates are cured for 90 min at 200° F. Following curing, half of the plates are treated with silane SIT8174 and the other half with SiCl<sub>4</sub>, followed by SIT8174, thereby converting the untreated M5 silica into hydrophobic/superhydrophobic and/or oleophobic particles. Following treatment with SIT8174 or SiCl<sub>4</sub>+ SIT8174 plates are cured for 30-60 min at 200° F. and subjected to assessment of water contact angle and Taber testing. Taber testing is conducted with a 250 g weight on the wheels. The end of superhydrophobic behavior was measured at roll-off angles of 6° and 9° as shown in Table 8a.

The contact angle data for before and after Taber testing is shown in Table 8b. Data for 6° water roll-off angle tests (see Example 1) after the indicated number of abrasion cycles on the Taber Abraser is plotted in FIGS. 3 and 4 for plates receiving 5, 10, 15, Or 20 ml of M5 silica at the indicated M5 to hexane weight to volume ratios. The data suggest that fillers increase the durability of the coating

TABLE 8a

Optimization of M5 Top Coat During Taber Testing				
	0.5 g M5 in 100 Hexane Amount of Taber Rubs	1.0 g M5 in 100 Hexane Amount of Taber Rubs	1.5 g M5 in 100 Hexane Amount of Taber Rubs	2.0 g M5 in 100 Hexane Amount of Taber Rubs
M5 Top Coat/Polane then 8174 Taber 250 g Rub Data at 6°				
5 ml per plate sprayed	100	200	500	500
10 ml per plate sprayed	400	300	600	600
15 ml per plate sprayed	400	500	600	700
20 ml per plate sprayed	500	500	600	600
M5 Top Coat/Polane then SiCl <sub>4</sub> and 8174 Taber 250 g Rub Data at 6°				
5 ml per plate sprayed	300	300	400	500
10 ml per plate sprayed	300	400	400	500

TABLE 8a-continued

Optimization of M5 Top Coat During Taber Testing				
	0.5 g M5 in 100 Hexane Amount of Taber Rubs	1.0 g M5 in 100 Hexane Amount of Taber Rubs	1.5 g M5 in 100 Hexane Amount of Taber Rubs	2.0 g M5 in 100 Hexane Amount of Taber Rubs
15 ml per plate sprayed	400	500	600	600
20 ml per plate sprayed	500	600	500	500
M5 Top Coat/Polane then 8174 Only				
Taber 250 g Rub Data at 9°				
5 ml per plate sprayed	200	300	600	600
10 ml per plate sprayed	500	400	700	700
15 ml per plate sprayed	500	600	700	800
20 ml per plate sprayed	600	600	700	700
M5 Top Coat/Polane then SiCl4 and 8174				
Taber 250 g Rub Data at 9°				
5 ml per plate sprayed	400	400	500	600
10 ml per plate sprayed	400	500	500	600
15 ml per plate sprayed	500	600	700	700
20 ml per plate sprayed	600	700	600	600

TABLE 8b

Contact Angle Data for Before and After Taber Testing															
M5 Top Coat/Polane Then 8174 Only															
0.5 g M5 in 100 Hexane				1.0 g M5 in 100 Hexane			1.5 g M5 in 100 Hexane			2.0 g M5 in 100 Hexane					
Contact Angle Before Taber 250 g															
Contact Angle Left	Contact Angle Right	Avg		Contact Angle Left	Contact Angle Right	Avg		Contact Angle Left	Contact Angle Right	Avg		Contact Angle Left	Contact Angle Right	Avg	
5 ml per plate sprayed 10 ml per plate sprayed 15 ml per plate sprayed 20 ml per plate sprayed	153.40	153.86	153.63	158.73	158.77	158.75	158.72	158.56	158.64	162.03	158.87	160.45			
	155.25	153.01	154.13	161.42	157.66	159.54	160.49	161.04	160.77	160.97	160.85	160.91			
	158.95	156.18	157.57	158.15	160.30	159.23	161.82	158.83	160.33	162.04	159.32	160.68			
	161.66	158.91	160.29	161.30	161.98	161.64	162.72	162.94	162.83	161.86	161.77	161.82			
M5 Top Coat/Polane then 8174 Only															
0.5 g M5 in 100 Hexane				1.0 g M5 in 100 Hexane			1.5 g M5 in 100 Hexane			2.0 g M5 in 100 Hexane					
Contact Angle After Taber 250 g															
Contact Angle Left	Contact Angle Right	Avg		Contact Angle Left	Contact Angle Right	Avg		Contact Angle Left	Contact Angle Right	Avg		Contact Angle Left	Contact Angle Right	Avg	
5 ml per plate sprayed 10 ml per plate sprayed 15 ml per plate sprayed 20 ml per plate sprayed	140.35	140.29	140.32	136.42	137.05	136.74	145.99	145.05	145.52	146.04	146.78	146.41			
	147.32	148.54	147.93	147.67	148.11	147.89	146.63	146.38	146.51	142.58	142.40	142.49			
	147.05	148.55	147.80	146.67	144.75	145.71	147.17	147.15	147.16	142.58	142.10	142.34			
	144.11	144.08	144.10	148.27	147.35	147.81	143.82	143.83	143.83	142.83	143.97	143.40			
M5 Top Coat/Polane then SiCl4 and 8174															
0.5 g M5 in 100 Hexane				1.0 g M5 in 100 Hexane			1.5 g M5 in 100 Hexane			2.0 g M5 in 100 Hexane					
Contact Angle Before Taber 250 g															
Contact Angle Left	Contact Angle Right	Avg		Contact Angle Left	Contact Angle Right	Avg		Contact Angle Left	Contact Angle Right	Avg		Contact Angle Left	Contact Angle Right	Avg	
5 ml per plate sprayed	152.44	151.44	151.94	155.19	156.01	155.60	158.10	160.33	159.22	159.95	159.66	159.81			

TABLE 8b-continued

Contact Angle Data for Before and After Taber Testing												
10 ml per plate sprayed 15 ml per plate sprayed 20 ml per plate sprayed	158.63	160.36	159.50	158.85	160.51	159.68	161.22	160.93	161.08	160.54	158.79	159.67
	159.49	157.62	158.56	160.73	157.20	158.97	161.92	162.12	162.02	162.75	159.10	160.93
	162.14	163.41	162.78	161.28	159.04	160.16	162.45	161.41	161.93	162.19	164.72	163.46
M5 Top Coat/Polane then SiCl4 and 8174												
	0.5 g M5 in 100 Hexane			1.0 g M5 in 100 Hexane			1.5 g M5 in 100 Hexane			2.0 g M5 in 100 Hexane		
	Contact Angle After Taber 250 g											
	Contact Angle Left	Contact Angle Right	Avg	Contact Angle Left	Contact Angle Right	Avg	Contact Angle Left	Contact Angle Right	Avg	Contact Angle Left	Contact Angle Right	Avg
5 ml per plate sprayed	145.71	145.84	145.78	148.70	149.69	149.20	146.07	146.56	146.32	144.40	146.65	145.53
10 ml per plate sprayed	148.46	147.22	147.84	148.69	148.61	148.65	147.90	147.61	147.76	147.95	147.82	147.89
15 ml per plate sprayed	148.29	146.70	147.50	146.39	147.57	146.98	144.57	146.55	145.56	146.39	148.10	147.25
20 ml per plate sprayed	148.93	148.62	148.78	147.69	147.97	147.83	147.54	148.23	147.89	146.50	148.67	147.59

## Example 8B

Initial water contact angle and Tabor Abraser durability measurements are conducted on 4 inch×4 inch aluminum plates base coated with POLANE® B and top coated with M5 silica suspended at a concentrations of 0.5 or 2% w/v. After curing the plates are treated with either SIT8174 or SiCl<sub>4</sub>+SIT8174 (SIT8174 10% solution in hexane and SiCl<sub>4</sub> 1% solution in hexane using 1 to 2 ml per 4×4 plate) as described above in Example 8a. Contact angle data for the plates with water droplets before Taber testing (250 g load) is plotted in FIG. 5. Each of the coatings has a contact angles greater than 150°, indicating that they display superhydrophobicity. Results for 6° and 9° roll-off angle analysis following Taber abrasion measurements are plotted in FIGS. 6 and 7 as a function of the volume of M5 suspension applied to the plates (ml/plates). FIGS. 8 and 9 plot the contact angle after Taber testing. For Taber testing using a 6° roll-off angle to assess the end of superhydrophobicity, the contact angle of water with the surface drops by about 15-20° at the point where the plate's performance is no longer considered superhydrophobic (test angles are <about 150°). Although, the plates are no longer considered superhydrophobic at the end of Taber testing (typical contact angles are between 140-148°), with angles greater than 120°, the Taber-tested coatings are still quite hydrophobic.

## Example 9

## Durable Superhydrophobic and Oleophobic Coatings Formed in a Single Step (One-Step) Process

Coatings displaying superhydrophobic and oleophobic behavior can be applied to surfaces in a single step process. Such processes may employ a binder to which second particles bearing an alkyl or haloalkyl group (covalently attached directly or indirectly, such as through a Si atom or a series of bonds through oxygen and silicon atoms) are added to the binder in the presence of about 5% of a block copolymer described below and an optional first particle (e.g., filler). Such compositions typically require thinning with a binder compatible solvent for spray application.

For this example, a block copolymer is prepared by reacting 3.13 g styrene, 1.92 g butyl acrylate, 12.32 g butyl methacrylate, 4.25 g glycidyl methacrylate, and 100 ml toluene in

a reaction flask with stirring at 85° C. A solution of 0.2 g AIBN in 2.5 ml toluene is added into the flask and mixture is maintained at 85° C. for 3 hours. A second amount of AIBN in toluene is added and the reaction is continued for another 3 hours. The reaction mixture is cooled at room temperature and the resulting acrylic polymer is precipitated with hexane, filtered, and dried under vacuum at 40° C. for 24 hr prior to use.

## Example 9A

## One Step Coatings Prepared with TS-720 Fumed Silica and Nanogel TLD201

Specific details of exemplary durable superhydrophobic/oleophobic coatings prepared on 4 inch by 4 inch aluminum plates employing a one-step process using the components given in Table 9a-1. Two plates employ fumed silica second particles (TS-720) treated with polydimethylsiloxane, two employ Nanogel TLD201, which is treated with hexamethyldisiloxane, and two employ Nanogel TLD201 and S60 glass particles as a filler. All plates are cured at 200 F for 90-120 min after air drying.

TABLE 9a-1

Details of One-Step Coating Process using POLANE® B, a Binder, and a Block Copolymer						
Sample	Polane® B (g)	Polymer (g)	Reducer (ml)	Silica Particles (g)		S60
				TS-720	Nanogel TLD201	
P-C-1	18	1.0	10	2.8		—
P-C-2	18	1.0	10	2.8		—
P-C-3	18	1.0	20	2.6		2.0
P-C-4	18	1.0	20	2.6		2.0
P-C-5	18	1.0	20		2.6	—
P-C-6	18	1.0	20		2.6	—

\*All plates were cured for 90-120 min at 200° F. in an electric oven.

All plates are tested for their durability and water contact angle. The durability is tested with the manual abrasion method (see Example 1) and also with a Taber machine employing a 250-g load. Data are summarized in Table 9a-2.

TABLE 9a-2

Durability Data using Hand Rub and Taber for Superhydrophobic Coatings Prepared by One-Step Process (See Table for Coating Details)												
Sample	Rub Method (g)		Rubs/Cycles (° Roll-Off)			CA Before			CA After			
	No.	Hand	Taber	3	6	9	Left	Right	Average	Left	Right	Average
P-C-1	800			40	60	80						
P-C-2		250		10	15	30	163.89	161.73	162.81	147.68	148.01	147.85
P-C-3	800			60	120	160						
P-C-4		250		20	70	100	163.74	162.19	162.97	148.49	147.36	147.93
P-C-5	800			80	160	300						
P-C-6		250		40	100	200	163.59	162.19	162.89	149.3	148.58	148.94

The durability data were taken for three roll-off angles of 3°, 6°, and 9°. The contact angle was measured before and after durability assessment with a Taber “Abraser”. The contact angle before abrasion testing for all six plates is between 161°-163°, implying that all of them are superhydrophobic as the contact angle with water exceeds 150° at room temperature. The coatings substantially retained their water repellant nature after abrasion, which was measured in two areas of the plates (left and right) before and after Taber abrasion testing.

#### Example 9B

One Step coatings prepared with HK400, HK400T and TLD201 Nanogel

Coatings displaying superhydrophobic and oleophobic behavior are prepared with a urethane binder (POLANE® B) to which are added the indicated second particles and a filler as described below. The compositions are thinned as required with a binder compatible solvent for spray applications.

HK400T nanoparticles (second particles) are prepared by treating ACEMATT® HK400 nanoparticles (Evonick Industries, distributed by The Cary Co., Addison, Ill.) with Gelest silanizing agent SIT8174.0 (tridecafluoro-1,1,2,2-tetrahydrooctyl)trichlorosilane. The particles (50-g) are prepared by stirring with a 400-ml of a 1% w/v solution in hexane for 6 hours. Hexane is allowed to evaporate away and residual hexane is removed by heating the mixture to 200° F. for 6 hours.

HK400T particles may also be prepared by pre-treating a 50 g sample of HK400 particles with 2 grams of Gelest silanizing agent SIT8174.0 (tridecafluoro-1,1,2,3-tetrahydrooctyl)trichlorosilane by blending the materials together in a mixer for 30 seconds. An additional 2 grams of the silanizing agent is added to the mixture and it is blended for 45 seconds further. The treated powder was placed in a PYREX® dish and dried at 200° F. for 12 hours.

Particles of TLD201 Nanogel, which are treated with hexamethyldisiloxane are used as purchased from Cabot Corp., Billerica, Mass.

First particles are selected from 512 Black (Size microns, Xiom Corp., West Babylon, N.Y.) and S60 glass bubbles (15-65 microns, 3M Corporation). For this Example, S60 glass bubbles are prepared by treating a 50-g batch of the glass bubbles with 1.25 ml of SIT8174.0 in 50 ml of solvent. The mixture is blended for about 1 to 2 hours followed by a baking for 3 hours at 200° F.

The details of the preparation of six 4 inch by 4 inch aluminum plates coated with a one-step process are set forth below (coatings 9b-1 to 9b-6). For each coating, the coated

plates are tested for contact angle and coating durability using both the manual abrasion method (see “hand rubs” see Example 1) and on the Taber Abraser unit with a 250-g load. Roll off angle data is obtained for both the manual abrasion and Taber sample testing at a 6° angle. Data for coatings 1-6 are summarized in Table 9b.

Coating 9b-1—A mixture of POLANE® B (6 ml), POLANE® A (1 ml), POLANE® Reducer (5 ml), HK400T second particles treated with SIT8174.0 (2 g) is prepared. For preparation of the mixture POLANE® B, POLANE® A and POLANE® reducer (6:1:5) is mixed thoroughly and the HK400T is mixed into the mixture. After the coating composition is mixed thoroughly, two aluminum plates are each sprayed with about 3.5 ml of the mixture and immediately cured at 200° F. for 2 hours.

Coating 9b-2—A mixture of POLANE® B (6 ml), POLANE® A (1 ml), POLANE® Reducer (8 ml), HK400T second particles treated with SIT8174.0 (1 g) and TLD201 second particles (0.75 g) is prepared. For preparation of the mixture POLANE® B, POLANE® A and POLANE® reducer (6:1:8), is mixed thoroughly and the HK400T and TLD201 are subsequently added to the mixture. After the coating composition is mixed thoroughly, two aluminum plates are each sprayed with about 3.5 ml of the mixture and immediately cured at 200° F. for 2 hours.

Coating 9b-3—A mixture of POLANE® B (6 ml), POLANE® A (1 ml), POLANE® Reducer (3 ml), HK400T second particles treated with SIT8174.0 (1 g) and 512 Black filler (1 g) is prepared. For preparation of the mixture POLANE® B, POLANE® A and POLANE® reducer (6:1:3), is mixed thoroughly and the HK400T and 512 Black filler are subsequently added to the mixture. After the coating composition is mixed thoroughly, two aluminum plates are each sprayed with about 3.5 ml of the mixture and immediately cured at 200° F. for 2 hours.

Coating 9b-4—A mixture of POLANE® B (6 ml), POLANE® A (1 ml), POLANE® Reducer (3 ml), HK400T second particles treated with SIT8174.0 (1.35 g) and S60 glass bubbles as a filler (1.35 g) is prepared. For preparation of the mixture POLANE® B, POLANE® A and POLANE® reducer (6:1:3), is mixed thoroughly and the HK400T and S60 filler are subsequently added to the mixture. After the coating composition is mixed thoroughly, two aluminum plates are each sprayed with about 3.5 ml of the mixture and immediately cured at 200° F. for 2 hours.

Coating 9b-5—A mixture of POLANE® B (6 ml), POLANE® A (1 ml), POLANE® Reducer (3 ml), HK400T second particles treated with SIT8174.0 (1 g) and S60 glass bubbles as a filler (1 g) is prepared. For preparation of the mixture POLANE® B, POLANE® A and POLANE®

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reducer (6:1:3), is mixed thoroughly and the HK400T and S60 filler are subsequently added to the mixture. After the coating composition is mixed thoroughly, two aluminum plates are each sprayed with about 3.5 ml of the mixture and immediately cured at 200° F. for 2 hours.

Coating 9b-6—A mixture of POLANE® B (6 ml), POLANE® A (1 ml), POLANE® Reducer (2 to 3 ml), POLANE® Accelerator (3 ml), HK400T second particles treated with SIT8174.0 (1.25 g) and S60 glass bubbles as a filler (0.7 g) is prepared. For preparation of the mixture POLANE® B, POLANE® A, POLANE® reducer and POLANE® Accelerator, is mixed thoroughly and the HK400T and S60 filler are subsequently added to the mixture. After the coating composition is mixed thoroughly, two aluminum plates are each sprayed with about 3.5 ml of the mixture and immediately cured at 200° F. for 2 hours.

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After the final thermal cure samples are tested for durability by using a Taber Abraser with a 250 g load. All samples are also tested to for end-of-life by determining the roll-off angle with a plate set a 6° incline at 25 abrasion cycle increments. End-of-life is determined by the propensity of more than half of a set of water drops (typically 20 drops per test set) to stick to the area subject to abrasion testing when the plate is set at a 6° degree angle from level.

Data for coatings prepared with S60 filler is summarized in Tables 10a and 10b. Table 10a gives the coating compositions leading to a S60 content from 10 to 60%. Table 10b sets forth the weight change as a measure of abrasion resistance obtained after the indicated number of abrasion cycles on a Taber Abraser apparatus. Data for coatings prepared with 512 Black filler is summarized in Tables 10c and 10d. Table 10c gives the coating compositions leading to a 512 Black content

TABLE 9b

Summary of Coating Details and Obtained Superhydrophobic Performance for One-Step Coating Process (All data is for 4 inch × 4 inch aluminum plates)												
One-Step Coating Details										Performance		
Polane (mL)					Particle Amount		Amount Sprayed	Cure	Contact	Hand	Taber	
Exp.	B	A	Reducer	Accelerator	Particle Type	(g)	(%)	per Plate	(° F./Time)	Angle	Rubs (800-g Load)	Rubs (250-g Load)
1	6	1	5		HK400 (SIT8174.0)	2	16.6	43.2	200/2 h	161	400-600	100-150
2	6	1	8		Treated HK400 (SIT8174.0)	1.0 + 0.15	6.67 + 5.0	43.2	200/2 h	165	500-600	100-125
3	6	1	3		Treated + TL.D201 Nanogel HK400 (SIT8174.0)	1.0 + 1.0	10.0 + 10.0	43.2	200/2 h	157	600-800	350-400
4	6	1	3		Treated + 512 Black HK400 (SIT8174.0)	1.35 + 1.35	13.5 + 13.5	43.2	200/2 h	160	Not Tested	200
5	6	1	3		Treated + S60 Glass Bubbles (SIT8174.0)	1.0 + 1.0	10.0 + 10.0	43.2	200/2 h	161	Not Tested	300
6	6	1	3	2	Treated HK400 (SIT8174.0)	1.25 + 0.70	12.5 + 7.0	43.2	200/2 h	162	1000+	500+
					Treated + S60 Glass Bubbles (SIT8174.0)							
					Treated							

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## Example 10

The effect of Filler content on the Performance of Durable Superhydrophobic Coatings (Optimizing Filler Effect on Superhydrophobic (SH) Coating Durability)

A set of 4 inch×4 inch aluminum plates are prepared by coating with a base coat comprising a mixture of POLANE® A and POLANE® B (1:6) containing the indicated amounts of either S60 glass beads (3M™, St. Paul, Minn.) or XIOM-512 black (Xiom Corp, West Babylon, N.Y.) filler (from 10% to 60% w/w). After the base coat applied to the plates had air dried, they were top coated with 10 ml per plate of untreated M5 fumed silica (particle size, Cabot Corp., Billerica, Mass.) as a 2% w/v suspension in hexane. The top coated plates are dried for 90 min at 93° C. After cooling, the plates are first treated with 1-2 ml of 10% SiCl<sub>4</sub> in hexane, and after the hexane has evaporated with 1-2 ml of the silanizing agent SIT 8174.0 (1% in hexane). All coating applications were made using an air spray gun. After all visible hexane evaporates, the plates are given a final thermal curing at 93° C. for 2-8 hours.

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from 10 to 60%. Table 10d sets forth the weight change as a measure of abrasion resistance obtained after the indicated number of abrasion cycles on a Taber Abraser apparatus. FIGS. 10a and 10b plot the number of abrasion cycles (Taber Abraser cycles) at the end-of-life (determined by a 6° degree roll-off analysis) as a function of the percentage of S60 or 512 Black in the coating composition. The data indicate that first particles can significantly enhance the performance of coatings.

TABLE 10a

Details Polane-binder preparations			
Polane Mixture	Polymer Solids (g)	Filler (S60 Glass) (g)	Percent S60 Comp
10.0 g	2.5 g	0.275	10
10.0 g	2.5 g	0.625	20
10.0 g	2.5 g	1.072	30
10.0 g	2.5 g	1.670	40

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TABLE 10a-continued

Details Polane-binder preparations			
Polane Mixture	Polymer Solids (g)	Filler (S60 Glass) (g)	Percent S60 Comp
10.0 g	2.5 g	2.500	50
10.0 g	2.5 g	3.750	60

TABLE 10b

Taber and Weight change data for various levels of S60 Glass filler						
% Comp	Taber Cycles at 6° end-of-life with 250 g load		Starting Weight (g)	Final Weight (g)	Weight Change (g)	Weight Change (%) per Taber Cycle
0	100	43.7847	43.774	0.0107	0.0244	0.00024
10	125	42.9316	42.9023	0.0293	0.0682	0.00055
20	175	43.1992	43.1704	0.0288	0.0667	0.00038
25	200	43.4265	43.3943	0.0322	0.0741	0.00037
30	225	43.1775	43.1453	0.0322	0.0746	0.00033
35	225	43.2781	43.2366	0.0415	0.0959	0.00043
40	150	43.3862	43.3402	0.0460	0.1060	0.00071
50	100	43.1617	43.1003	0.0614	0.1423	0.00142
60	75	43.0674	42.974	0.0934	0.2169	0.00289

TABLE 10c

Details Polane-binder preparations			
Polane Mixture	Polymer Solids (g)	Filler (512 Black) (g)	Percent 512 Comp
10.0 g	2.5 g	0.275	10
10.0 g	2.5 g	0.625	20
10.0 g	2.5 g	1.072	30
10.0 g	2.5 g	1.670	40
10.0 g	2.5 g	2.500	50
10.0 g	2.5 g	3.750	60

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TABLE 10d

Taber and Weight change data for various levels of 512 thermoplastic filler						
% Comp	Taber Cycles at 6° end-of-life with 250 g load		Starting Weight (g)	Final Weight (g)	Weight Change (g)	Weight Change (%) per Taber Cycle
0	100	43.7847	43.774	0.0107	0.0244	0.00024
10	200	43.775	43.748	0.0270	0.0617	0.00031
20	300	43.7771	43.7394	0.0377	0.0861	0.00029
30	350	43.847	43.8045	0.0425	0.0969	0.00028
40	500	43.5426	43.489	0.0536	0.1231	0.00025
50	500	43.8899	43.8331	0.0568	0.1294	0.00026
60	250	44.6785	44.617	0.0615	0.1377	0.00055

## Example 11

## Powder Coat Binder System for SH and OP Surfaces

## 11a) Two Part Superhydrophobic and Oleophobic Powder Coatings

Aluminum plates, 4 inches by 4-inches are used as test objects for assessment of powder coating binder systems. Table 11a summarizes some results obtained from the use of two powder coatings as binders for the preparation of HP/OP coatings and surfaces; GLSS70, a clear powder from Innatek Powder Coatings LLC (Big Spring, Tex.) and Tiger 39/80170 Black wrinkle powder (TIGER Drylac U.S.A., Reading, Pa.).

In each case, dry powders are sprayed on the aluminum plates as a base coat, followed by heating until the powder coatings begin to melt (details of the application are given in Table 11a). At the melt point, a top coat comprising fumed silica treated with polydimethylsiloxane (TS-720 CAB-O-SIL TS-720, Cabot Corp., Billerica, Mass. as a 4.2% or 2.1% suspension in acetone is applied to the base coat by spraying. The top-coated plates are heated to 400° F. (about 200° C.) for 10 min. Plates treated with Innatek powder coating resulted in superhydrophobic behavior and achieved about 325 cycles (rubs) in the manual abrasion test conducted as in Example 1. Manual abrasion testing of sample 3, which was prepared with a top coating that contained 5% TS-720 and 20% of the Innatek base coat powder by weight, resulted in similar abrasion behavior (resistance to 325 abrasion cycles in the manual test). Tiger Black wrinkle powder also produced superhydrophobic coatings with lower abrasion resistance the manual abrasion test described in Example 1 (about 50 abrasion cycles). Overall, the highest durability based on this data arises when surfaces are heated to just above the powder coat melting point prior to applying the base and top coats, and curing of the top coat at a temperature near the melting point of the powder coat for about 2-3 min.

TABLE 11a

The Use of Powder Coatings as Binder for the Formation of Superhydrophobic, Hydrophobic and/or Oleophobic Coatings				
Base Coat	Pretreatment	Top	Cure Treatment	Rubs w/Hand Tool (800-g Load)
1. Innatek GLSS 70 Clear Powder(dry spray)	Heat until powder just begins to melt top coat	4.2% TS-720 in Acetone	400° F.-10 min	325



TABLE 11a-continued

The Use of Powder Coatings as Binder for the Formation of Superhydrophobic, Hydrophobic and/or Oleophobic Coatings				
Base Coat	Pretreatment	Top	Cure Treatment	Rubs w/Hand Tool (800-g Load)
2. Tiger 39/80170 Black Wrinkle Powder (dry spray)		4.2% TS-720 in Acetone	400° F.-10 min	50
3. Innotech GLSS70 Clear Powder (dry spray)		5% TS-720 20% GLSS70 in Acetone	400° F.-10 min	350
4. Innotech GLSS70 Clear Powder	Preheat base plate to 400° F. and immediately dry spray base coat and immediately top coat	4.2% TS-720 in Acetone	400° F. until melted	500-750
5. Innotech GLSS70 Clear Powder (spray dry base on cold plate)	Heat it to 400° F. until it begins to melt and apply top coat	4.2% TS-720 in Acetone	400° F.-2-3 min	200
6. Innotech GLSS70 Clear Powder (spray dry base on preheated plate)	Preheat plate to slightly above 400° F. before dry spraying base coat followed by immediate top coat	4.2% TS-720 in Acetone	400° F. until melted	825
7. Innotech GLSS70 Clear Powder	Preheat base plate to 400° F. before spraying base coat and immediately top coat (Preheat temperature may be below 400° F.)	2.1% TS-720 in Acetone	400° F. until melted Heated 5 additional minutes at 400° F.	300 300

## 11b) Performance of Two Part Superhydrophobic and Oleophobic Powder Coatings

Table 11b summarizes further results with powder coatings. Again, aluminum plates, 4 inches by 4-inches are used as test objects for assessment of powder coating binder systems employing white Innotech powder coat G17SG101S70, (Innotech Powder Coatings LLC, Big Spring, Tex.). Plates are coated with G17SG101S70 applied to a cold plate, which is heated 10 min at the indicated temperatures, followed by a top

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coating with suspension of 4.2% TS-720 (fumed silica treated with polydimethylsiloxane) in the indicated solvent, and a final cure of at about 400° F. (see table). Manual abrasion testing conducted as in Example 1 indicated that some samples could resist over 900 abrasion cycles. When heating and cooling cycles are used prior to top coat application, some variation in the abrasion resistance can arise due to the extent of cooling the surfaces have experienced at the time of the top coat application (see e.g., samples 8 and 9).

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TABLE 11b

Experimental Coating Details for Use of Powder Coats as Binder Systems for Preheat Temperature Optimization				
Base Coat	Pretreatment	Top	Cure Treatment	Rubs w/Hand Tool (800-g Load)
1. Innotech G17SG101S70 White Powder	Spray base coat and heat to 225° F. and spray top coat	4.2% TS-720 in Acetone	400° F.-5 min	925
2. Innotech G17SG101S70 White Powder	Spray base coat and heat to 242° F. and spray top coat	4.2% TS-720 in Ethanol	Heat to 387° F. surface temperature Heat to 392° F.	300
3. Innotech G17SG101S70 White Powder	Spray base and heat to 230° F. and spray top coat (plates had cooled to 149° F. when put in for final heat)	4.2% TS-720 in Acetone	Heat to 392° F.	600
4. 90-1009 R-H Powder	Spray base and heat to 243° F. and spray top coat	4.2% TS-720 in Acetone	460° F.-15 min	200
5. Innotech G17SG101S70 White Powder	Spray base and heat to 175° F. and spray top coat	4.2% TS-720 in Hexane	400° F.-6 min	850
6. Innotech G17SG101S70 White Powder	Spray base and heat to 300° F. and spray top coat	4.2% TS-720 in Hexane	400° F.-6 min	250

TABLE 11b-continued

Experimental Coating Details for Use of Powder Coats as Binder Systems for Preheat Temperature Optimization				
Base Coat	Pretreatment	Top	Cure Treatment	Rubs w/Hand Tool (800-g Load)
7. Innotek G17SG101S70 White Powder	Spray base and heat to 250° F. and spray top coat	4.2% TS-720 in Hexane	400° F.-6 min	800
8. Innotek G17SG101S70 White Powder	Spray base and heat to 200° F. and let cool and apply top coat	4.2% TS-720 in Hexane	400° F.-6 min	150
9. Innotek G17SG101S70 White Powder	Spray base and heat to 200° F. and let cool and apply top coat	4.2% TS-720 in Hexane	400° F.-6 min	750

Results of testing 90-1009R-H under similar conditions indicated that while superhydrophobic and oleophobic surfaces can be formed with that the material did not perform as well in abrasion testing. (data not shown)

#### Example 12

#### Effects of First Particles on Hydrophobic, Superhydrophobic and/or Oleophobic Powder Coat Performance

Aluminum plates, 4 inches by 4-inches, are coated with Innotek G17SG101S70 containing the indicated first par-

titles as a base coating. The first particles employed are selected from (1) extend spheres SL-150 (3M™, St. Paul, Minn.), (2) S60 HS glass bubbles (3M™, St. Paul, Minn.), (3) R&H 90-1009 Kynar plastic (Rohm & Haas, Philadelphia, Pa.), and (4) S/G extendo spheres (3M™, St. Paul, Minn.). The base coat was heated to 200-210° F., prior to applying a top coat of 4.2% TS-720 (fumed silica treated with polydimethylsiloxane) suspended in hexane. Plates bearing the top-coat are given a final cure at 400° F. for 6 min

TABLE 12a

The Preparation and Performance of Coatings Prepared With Powder Coating Binder Systems					
Base Coat	Filler	Pretreatment	Top	Cure Treatment	Rubs w/Hand Tool (800-g Load)
1. Innotek G17SG101S70 White Powder	Extendo spheres SL-150 10% in Innotek base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	950
2. Innotek G17SG101S70 White Powder	S60 HS glass bubbles 10% in Innotek base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	650
3. Innotek G17SG101S70 White Powder	S60/10000 glass bubbles 10% in Innotek base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	700
4. 90-1009 R-H Powder	R&H 90-1009 Kynart plastic 10% in base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	750
5. Innotek G17SG101S70 White Powder	Extendo spheres SL-150 - 10% bubbles in base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	700
6. Innotek G17SG101S70 White Powder	Extendo spheres SL-150 15% in base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	1100
7. Innotek G17SG101S70 White Powder	Extendo spheres SL-150 20% in base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	1200
8. Innotek G17SG101S70 White Powder	Extendo spheres SL-150 25% in base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	1800
9. Innotek G17SG101S70 White Powder	Extendo spheres SL-150 30% in base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	1200
10. Innotek G17SG101S70 White Powder	Extendo spheres SGC1367 10% in Innotek base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	1100

TABLE 12a-continued

The Preparation and Performance of Coatings Prepared With Powder Coating Binder Systems					
Base Coat	Filler	Pretreatment	Top	Cure Treatment	Rubs w/Hand Tool (800-g Load)
11. Innotek G17SG101S70 White Powder	Extendo spheres SGC1367 15% in base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	1300
12. Innotek G17SG101S70 White Powder	Extendo spheres SGC1367 20% in base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	900
13. Innotek G17SG101S70 White Powder	Extendo spheres SGC1367 25% in base	Spray base coat and heat surface to 200-210° F.	4.2% TS-720 in Hexane	400° F.-6 min	1000

Table 12b: The Preparation and Performance of G17SG101S70 Powder Coating as a Binder

Aluminum plates, 4 inches by 4-inches, preheated to 210° F. are coated with a base coat of Innotek G17SG101S70 containing SL-150 extendo spheres, 25% weight to volume at

the indicated coverage rates (weight after drying at 200-210° F.). After top coating with TS-720 as indicated the plates are cured at about 400° F. and subject to abrasion testing. All abrasion testing data are obtained using the manual abrasion test described in Example 1, see Table 12b.

TABLE 12b

Experimental Coating Details for Use of Powder Coats as Binder Systems for Relative Amounts of Base and Top Coats					
Base Coat	Filler	Pretreatment	Top	Cure Treatment	Rubs w/Hand Tool (800-g Load)
1. Innotek G17SG101S70 White Powder	Step 1: Extendo spheres SL-150 25% in base Sprayed 12.03 g of this as base coat	Heated surface to 210° F.	4.2% TS-720 in Hexane Applied once after 210° F. Go to Step 2	400° F.-7 min	1600
	Step 2: Applied 13.82 g of base coat of above blend again		4.2% TS-720 in Hexane		
2. Innotek G17SG101S70 White Powder	Step 1: Extendo spheres SL-150 25% in base Sprayed 11.88 g of this as base coat	Heated surface to 215° F.	4.2% TS-720 in Hexane Applied once after 210° F. Go to Step 2	400° F.-7 min	1000
	Step 2: Applied 3.71 g of base coat of above blend again		4.2% TS-720 in Hexane		
3. Innotek G17SG101S70 White Powder	Extendo spheres SL-150 25% in base Sprayed 11.98 g of this as base coat	Heated surface to 205-215° F.	4.2% TS-720 in Hexane	400° F.-7 min	1100
4. Innotek G17SG101S70 White Powder	Extendo spheres SL-150 25% in base Sprayed 8.74 g of this as base coat	Heated surface to 205-215° F.	4.2% TS-720 in Hexane	400° F.-7 min	1300
5. Innotek G17SG101S70 White Powder	Extendo spheres SL-150 25% in base Sprayed 5.97 g of this as base coat	Heated surface to 205-215° F.	4.2% TS-720 in Hexane	400° F.-7 min	1600

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## Example 13

## SH and OP Effect Surface Preparation Using Thermal Deposition Processes

Aluminum or carbon steel plates 6 inches×6 inches×0.25 inches are sprayed with one of the materials recited in Table 13 using thermal (high-velocity oxyfuel (HVOF)) application processes. In all cases, excellent bonding of the sprayed materials to both aluminum and steel substrates is noted. The deposited surface was resistant to scratched, even when pressed with a sharp hardened metal objects (e.g., scissors). As deposited, coatings uniformly covered the surface giving rise to a sandpaper-like texture with the degree of coarseness depended on the size of the powder employed.

TABLE 13a

Materials and Thermal Spray Processes used to Prepare Test Plates	
Material	Thermal Spray System
Zirconia stabilized	Rokide gun
Al <sub>2</sub> O <sub>3</sub>	Rokide gun
80-20 Ni—Cr	Rokide gun
316 Stainless steel	HVOF
Tungsten carbide/cobalt	HVOF
Chromium carbide/nickel	HVOF
Nickel aluminide (IC-50)	HVOF

The surfaces prepared using the HVOF-spray process are treated by brushing on SIT8174 silane (Gelest, Inc., Pottstown, Pa.) as a 1% solution in hexane. Alternatively, the surfaces of some plates are sprayed with a suspension of polydimethylsiloxane treated fumed silica (TS-720, 4.2% w/v in hexane) as opposed to treatment with the silanizing agent SIT8174. Following application of the indicated silane or fumed silica, the plates are cured at room temperature for 24 h. After curing, all metal surfaces are found to be superhydrophobic, irrespective of the metallic or metal oxide coating applied. The surface treatment given to plates and the results from manual abrasion testing determined as in Example 1 are given in Table 13b.

TABLE 13b

Rub Durability Data for Superhydrophobic Coatings Prepared by Thermal Spray Processes				
Material	Rubs using Hand Tool (800-g Load)			
	Silane SIT8174		Silane SIT8174 + 4.2% TS-720 in Hexane	
	Aluminum	Steel	Aluminum	Steel
ZrO <sub>2</sub> Stabilize	—	500	750	—
Al <sub>2</sub> O <sub>3</sub>	300	300	600	550
316SS	—	—	820	1000
W-Carbide-Co	—	350	400	—
Cr-Carbide-Ni	200	200	600	—
IC-50	400	350	700	—

## Example 14

## Coating Application Methods and Exemplary products

The polymer coatings described herein may be applied by spraying, brushing or dipping objects to be coated. Using

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such methods polymer based coatings may be applied to both simple and complex shaped surfaces;

Coatings applied to simple and complex surfaces by spray-on processes include both one step and two step coatings. The coatings can be applied to surfaces for a variety of purposes including corrosion resistance and reduced resistance to water flow (drag). The SH coating can be applied to reduce water film formation and accumulation of condensation, even on surfaces with complex shapes such as steam turbine blades. The SH coatings can also be applied where high durability and corrosion resistance is desired, such as on slip resistant flooring in demanding environments

Coatings may also be applied by dipping object including electrical switches of the type used in food industry processing and packaging lines. Non-wetting SH coatings are particularly suitable for such facilities as they are typically cleaned by washing on a daily basis, and water seepage into switches can cause current leakages or shorts leading to unwanted production line shutdowns. The switches may be coated in a two step process with Self-Etching Primer or POLANE® as the binders.

Where dipping is not a suitable alternative, coatings may be applied by painting or brushing coatings on the surface. One example of an object that is suited to coating by brushing or painting of coatings is heat exchanger for clothes dryers. A coating of Self-Etching Primer with a top coat of 4% of TS-720 in ethanol is applied by a two step process and is anticipated to keep lint from accumulating on the heat exchanger.

## Example 15

## Resistance to Ice Formation and Adherence to Coated Surfaces

Aluminum plates 4 inches by 4-inches are prepared and one is coated with a superhydrophobic coating of POLANE® B containing 20% S60 glass bead filler as base coat with 4% TS-720 in hexane as top coat applied in a two step process. Both plates are cooled to about −20° C. for 1 hour in a refrigerated enclosure. Water is cooled to until ice formation starts (0° C.). The cooled water is dropped on to the uncoated and coated plates so that it runs down the surface to determine if the cooled surfaces permit ice formation and adherence. Significant amounts of the cooled water freeze on to the uncoated aluminum plate. In contrast, water running down the surface of the plate coated with the superhydrophobic coating has little if any ice form on it. Moreover, the ice which does form on the coated plate is not tightly bound and readily comes loose, which contrast to the results observe with the uncoated aluminum plate.

## Example 16

## Coating Electric Transmission Cable

16a) Individual segments (12-inches long) of 19 strand aluminum electrical transmission cables are spray coated using a two-step coating process. The first coat consisted of POLANE® A: POLANE B® (1:6 v/v) and POLANE® reducer as needed for ease of spraying) to which 20% w/v of 512 black thermoplastic filler is added. The top coat consisted of a 4% M5 (w/v) silica that is pretreated with Gelest Silane SIT8174.0 (Example 5, Method B) suspended in hexane. After coating, the cables were cured at 93° C. for 60 min in an electric oven.

The coated cable segments are all superhydrophobic with contact angles exceeding 150° (visual examination).

#### 16b) Flexibility at Ambient Temperature (23° C.)

A segment of cables prepared in 16a is bent to 35° to simulated coiling operation. Bending to a 35° angle does not produce any delamination, cracking, chipping, or peeling of the coating, or degradation of superhydrophobic performance

#### 16c) Flexibility at Freezing Temperatures (−30° C.)

A segment of the coated cable prepared in 16a is cooled in the freezer to about −29° C. (about −20° F.) for about 1.5 hours and then bent to an angle of 48°. Bending to that angle does not produce any flaking or delamination. Bend angles exceeding 35°, however, do tend to cause the individual strands of the cable to separate, and create openings large enough for water to enter the cable.

#### 16d) Superhydrophobicity and Thermal Cycling

An unbent (straight) segment of the coated cable is subjected to a thermal cycling test. The cable is placed on a hot plate and the cable temperature is monitored by a non-contact temperature gun. When cable surface temperature reaches 170° C., it is removed from the hot plate and cooled to room temperature (about 18° to 23° C.) using an air gun. The same cycle is repeated 10 times with no loss of superhydrophobicity. Thermal cycling testing data is presented in Table 16.

TABLE 16

Thermal Cycling Data on Superhydrophobic Coated Electrical transmission cable				
Thermal Cycle #	Time at Temperature	Temperature deg C.	Time after Air Cooling	Temperature deg C.
1	10:21	170	10:25	23
2	10:27	170	10:29	22
3	10:31	170	10:33	23
4	10:35	170	10:37	23.5
5	10:39	170	10:41	23
6	10:43	170	10:45	23.8
7	10:47	170	10:49	22.9
8	10:51	170	10:53	20
9	10:55	170	10:57	21
10	10:59	170	0:14	21

#### Example 17

##### The preparation of Superhydrophobic, Hydrophobic and/or Oleophobic Tapes, Ribbons, or Sheets

Superhydrophobic, hydrophobic and/or oleophobic tapes, ribbons and sheets can be prepared using any flat, essentially two-dimensional material. In some embodiments the sheets can have an adhesive applied to one surface (see Example 17a) prior to applying the hydrophobic, superhydrophobic, or oleophobic coating, or can be coated with adhesive on the opposing surface after superhydrophobic, hydrophobic and/or oleophobic coating applications have been conducted (see Example 17b). The two dimensional materials can be in the form of sheets or narrow strips (e.g., adhesive strips that can be formed into rolls after their preparation or “tapes”) or even patterns, that can be made out of any suitably flexible material including, but not limited to, metals such as aluminum or tin, fiberglass, or plastic.

The materials are treated to increase the hydrophobicity/oleophobicity of at least a portion of one (or possibly both surfaces) and even the edges, which have nominal area.

#### Example 17A

Tapes and sheets (e.g., adhesive sheets) may be prepared from materials essentially two dimensional materials that are have an adhesive coating on one side (“pre-glued”). In some embodiments the pre-glued surface is covered with paper or other film that can be peeled away to expose the adhesive.

The surface(s) of the materials not bearing the adhesive are treated to increase the hydrophobicity and/or oleophobicity. In some embodiments hydrophobicity and/or oleophobicity is increased using polymer coatings employing binders such as those described in Examples 2 through 12. In such process, tape surfaces are sprayed with polymeric binders including Self-Etching Primer, POLANE® B, LUMIFLON® using one-step or two step processes. Where two-step processes are employed, the top surface of the binder layer (base coat) is coated with either a treated fumed silica or silica nanogel (e.g., silicas such as TS-720 treated with agents that produce hydrophobic or oleophobic behavior). Where a fumed silica or silica nanogel is untreated with agents that provide hydrophobic or superhydrophobic properties, the fumed silica or silica nanogel can be treated with a reagent (e.g., silanizing agent such as SIT8174 from Gelest, Pottstown, Pa.) to increase the hydrophobicity and/or oleophobicity of the surface after silica application to the binder. The application of agents to increase the hydrophobicity and/or oleophobicity of untreated fumed silica or silica nanogels applied to the binder is typically conducted after 24 hours of room temperature curing of the binder/silica composite. The agents (e.g., silanizing agents such as SIT8174) may be applied by any suitable method including brushing or spraying as described above.

Where the polymer binder contains one or block copolymer polymers and particles of fumed silica or silica nanogel treated with agents that produce hydrophobic, superhydrophobic and/or oleophobic behavior (e.g., TS-720 or other silicas treated with silanizing agents bearing hydrophobic functionalities) the materials may be coated in a one-step process. In such a process the binder, block copolymer and treated silica(s) are mixed in and the entire blend is applied to the desired materials surface and cured under ambient (room temperature) conditions.

To speed the curing process the tapes, ribbons or sheets may be warmed to temperatures that do not affect the adhesive or binder (e.g., causing either the adhesive or binder to melt, flow to locations where it was not originally applied, or become brittle).

The surfaces of tapes, ribbons and sheets treated in the above-described manner will generally be hydrophobic if silanizing agents bearing alkyl functionalities are employed. The same surfaces will generally display superhydrophobic and oleophobic behavior where silanizing agents have fluorinated alkyl groups at the end furthest from the Si atom to which they are attached.

#### Example 17B

Ribbons and sheets of hydrophobic, superhydrophobic, and oleophobic materials may be prepared from essentially two dimensional materials that are have an have no adhesive coating on any side prior to the application of hydrophobic, superhydrophobic and/or oleophobic coatings (“non-glued” sheets and ribbons). Ribbons and sheets may be used with out

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the application of adhesives or may have adhesives applied subsequent to the applications of coatings (e.g., converting ribbons into tapes). The same processes may be used for making sheets and ribbons of materials hydrophobic, super-hydrophobic and/or oleophobic that are employed for the preparation of pre-glued tapes and sheets described in Example 14a can be employed. When applied, adhesives can be applied by any known means, including spraying, brushing or rolling the materials on surfaces. Surfaces having adhesives applied may be protected by the application of an easily removable material such as a separating paper applied to the adhesive coated surfaces.

## Example 18

The Use of Durable HP/OP Coatings or Tape or Ribbons Comprising a Durable HP/OP Coating to Form Spill-Resistant Borders.

## Example 18A

## A Durable HP/OP Coatings as Spill Resistant Border

Around the outer perimeter of a 4 inch by 4 inch glass plate, a one half-inch border of Polane B containing first particles of XIOM 512 thermoplastic (10-100 microns) about 20% by weight is applied as a base coat. A top coat of TS-720 silica (Cabosil, Billerica, Mass.) as a 4.5% w/v suspension in ethanol is applied. The plate is air dried in followed by curing at 200° F. for 30-60 min. The plate retains water to a height greater than 5 mm as determined by the method in part b of this example.

## Example 18B

## Adhesive Aluminum Tape Coated with an HP/OP Coating as a Spill Resistant Barrier

Aluminum tape, about one-half inch wide coated with the Polane based coating is applied around the top outside edge of a 4 inch by 4 inch square aluminum plate to form a spill-resistant border. The plate is tested for its water retaining capacity, by filing the plate at its center with water until the water overflowed the tape border. The height of water retained by the tape barrier was determined by dividing the volume of water retained by the plate by the area of the plate within the border. A water height of about 5.7 mm, can be retained on aluminum plates prepared as described. In the absence of a hydrophobic/superhydrophobic tape border, or in the presence of an untreated aluminum tape border, aluminum plates will not retain significant amounts of water.

## Example 19

## Hydrodynamic Drag Reduction

Two 24 inch×48 inch×3/8 inch aluminum plates (Plate A and Plate B) for drag reduction testing were prepared as follows:

Both Plates A and B were prepared using Self-Etching Primer as the binder with 4% w/v of 512 thermoplastic (10-100 μm) as the filler. The base coat used 18 ml of binder/filler mixture per square foot. Following the air gun spraying of the base coat, the plates were sprayed with a top coat of 4.2% of TS-720.

Plate A was heated at 400° F. for 10 min in a continuous infrared oven. This plate had a brownish surface appearance.

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Plate B was air dried and tested in this condition. This plate had a gray-white color after drying.

The plates are assessed for water droplet contact angle hysteresis, surface air fraction, hydrodynamic drag reduction, and related parameters.

## Example 19A

## Contact Angle and Contact Angle Hysteresis

Water droplet contact angles and hysteresis are determined using deionized water (~5 μL in volume, ~2 mm in diameter for a spherical droplet) on both Plate A and Plate B using a KSV CAM 100 contact angle meter. Table 19a summarizes the results.

TABLE 19a

Summary of Test Results						
Sample Type	Base Material	Number of Samples	Number of trails	Contact Angle (°)	De- viation	Hysteresis
Plate A	Aluminum	2	2	140.34	±0.24	6.73 ± 2.5
				136.90	±0.41	
Plate B	Aluminum	2	2	161.98	±4.06	15.37 ± 2.5
				161.63	±0.45	

The surface morphologies of the coatings on Plates A and B are also examined using a scanning electron microscope. The surface morphology of Plate A is rougher than that of Plate B, suggesting that the higher contact angle on the Plate B is due to its higher surface roughness.

## Example 19B

## Projected Surface Air Fraction

Projected surface air fraction was determined based upon the contact angle assessment in Examples 19a by using the Cassie-Baxter equation ( $\cos \theta = f_{SL} \cos \theta_0 - 1 + f_{SL}$ , where  $\theta$  denotes an apparent contact angle on an interface of solid and gas,  $f_{SL}$  a fraction of wet surface (i.e., solid-liquid fraction), and  $\theta_0$  a contact angle on a referential smooth rolled aluminum surface).

The estimated air (gas) fraction ( $f_{LG} = 1 - f_{SL}$ ) on the super-hydrophobic surface of Plates A and B, which is a critical factor influencing hydrodynamic drag reduction, is summarized in Table 19b. That table summarizes the expected surface air fraction of the coated plates. The surface air fractions are estimated for varying referential contact angles ( $\theta_0 = 80 - 110^\circ$ ) for a smooth surface. The results suggest that higher drag reduction effect would be achieved with Plate B due to the higher air fraction.

TABLE 19b

Expected Surface Air Fraction			
Substrate	Apparent Contact Angle (°) (Ave.)	Reference Contact Angle (°)	Surface Air Fraction, $f_{LG}$
Plate A	140	80	0.801
		90	0.766
		100	0.717
		110	0.644
Plate B	161	80	0.954
		90	0.946
		100	0.934
		110	0.917

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## Example 19C

## Measurement of Hydrodynamic Drag of SH-Coated Flat Plates

The hydrodynamic drag reduction of plates A and B are measured in a high-speed water towing tank system employing a monorail supported, cable driven, sample support capable of speeds of 0-60 ft/s). FIG. 11 panels (a) and (b) show the results of testing plates A and B at various water flow speeds covering both laminar and turbulent flows. Three plates were tested (Control: smooth reference surface with no coating, Plate A and Plate B).

The measured drag and the drag reduction observed for the plates relative to the control plate is plotted FIG. 11(b). The drag was increased on Plate A (compared to that of a smooth control surface, suggesting that the surface of the Plate A is wetted and that there is no slip effect due to the presence of surface air. The surface coating on Plate A creates an effective surface roughness of 0.0016, using the ITTC (International Towing Tank Conference) friction line for a standard fully turbulent friction coefficient. The superhydrophobic coating of Plate B (achieves a significant drag reduction, up to 30%, especially at low speeds where the flow is laminar. Plate B is tested twice, the first data set is by varying the water speed from a low to high. For the second set of data for Plate B was obtained by varying the water speed from high to a low. Both tests show the drag reduction at the low speed for Plate B.

Drag reduction at lower speed is tested on Plate B beginning at lower speeds than the data used in FIG. 11. FIG. 12 is a plot of the measured drag (Panel (a)) and the drag reduction (Panel (b)) observed for the coated Plate B with respect to a smooth control surface. As with the low speed water data plotted in FIG. 8, the data which is plotted in FIG. 9 show significant drag reduction in the range of 30% at the low speed.

Inspection of Plates A and B following hydrodynamic drag measurements reveals the presence of air bubbles, typically 0.1-0.3 mm in size, were retained on Plate B. In contrast to Plate B, Plate A did not retain a coating of such bubbles.

## Example 20

## Superhydrophobic Coating Durability Testing by Ultrasonic Technology

Samples are coated using a two step process. The base coat employs POLANE® B as a binder and Corvel Black as filler; and is followed by a top coat of M5 silica pretreated with Gelest silanizing agent SIT8174 (Example 5, Method B) suspended at 4% w/v in hexane. The coated sample is submerged in tetrahydrofuran (THF) and sonicated for 10 min using a UP400S Sonicator from Hielscher-Ultrasound Technology, Ringwood, N.J., (400 W, 24 kHz unit run at 100% amplitude and for a single 10 min cycle). Following sonication, the coatings are dried and found to be completely intact with no loss of superhydrophobic performance (water contact angles of at least 150°).

## Example 21

## Liquid Nitrogen Testing of Superhydrophobic Coatings

Two aluminum plates are coated using a two step process. The first plate (A) is coated with POLANE® B and S60 glass beads as base coat, followed by the application of M5 pretreated with Gelest silane SIT8174 (Example 5, Method B) suspended at 4% w/v in hexane as the top coat. A second

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aluminum plate (b) is coated in an identical fashion as the first substituting 512 thermoplastic beads for the S60 glass beads as the filler.

The plates are cooled in liquid nitrogen (-196° C.) and subjected to a bend test in which the plates are bent several degrees at a time as rapidly as possible with repeated cooling in liquid nitrogen to reach the indicated angles. The first plate was successfully bent to an angle of 120° without noting any delamination or cracking of the coating. The second plate was successfully bent to an angle of 140° without delamination or cracking of the coating. Both plates retain their superhydrophobicity after liquid nitrogen cooling and bending.

## Example 22

## Superhydrophobic Coatings Applied to a Flexible Rubber Surface

As a test of the ability to coat flexible surfaces, a toilet plunger with a rubber end is coated using a two step process using POLANE® B and S60 glass beads as base coat, followed by the application of M5 pretreated with Gelest silane SIT8174 (Example 5, Method B) as the top coat. The coating is applied to the plunger's rubberized end (both inside and outside) and the adjacent portion of the handle to the extent that it will become wet in use. The coated plunger is cured at room temperature for 24 hours.

The plunger is subject to repeated cycles of plunging (50 uses) without showing any wetting or damage to the coating on the plunger head or the handle area. The coated plunger minimized or eliminated dripping and surface contamination by materials that could adhere to the plunger in use.

## Example 23

## Superhydrophobic Coatings Applied to Bed Pans and Bedside Commodes

A bed pan made from polypropylene is coated using a two step process using POLANE® B and S60 glass beads as base coat, followed by the application of M5 pretreated with Gelest silane SIT8174 (Example 5, Method B) as the top coat. The coating is applied both inside and outside.

A bedside commode made of high density polyethylene is coated in the same fashion as the bed pan.

The coated bed pan and commode do not become wet during use and avoids the adherence of fecal matter to their surfaces. Treated pans and commodes are easier than their untreated counterparts to clean, which avoids the need for pressure washing and the spreading of bacteria from incompletely cleaned surfaces.

## Example 24

## Science Fun and Training Kits Application of Superhydrophobic Coating

The superhydrophobic phenomenon may not only be employed in many useful and interesting applications, but it also serves the purpose of science education and training in areas including: Second particles and nanotechnology; surface tension; contact angles and their measurement; solvents; and methods of preparing and applying superhydrophobic coatings.

Kits are assembled comprising a one-step coating composition and instructions. Alternatively kits are assembled to comprise the materials needed to applying a superhydrophobic coating in a two-step process and instruction.

Kits may further include on or more of: applicators, such as paint brushes; mixing implements; and containers.

In addition to providing coating materials and instructions on how to apply the coating, the instructions may also include information on how to observe superhydrophobic phenomena and/or the basic scientific method.

### Example 25

#### Evaluation of Surface Roughness and Coating Thickness

A series of coatings prepared by the methods described herein are evaluated for roughness using a Mahr PocketSurf

PS1 from Mahr Federal Inc. (Providence, R.I. 02905) and for thickness using a Positector 6000 from Delfelsko Corp. (Ogdensburg, N.Y.). Both the arithmetical mean roughness (Ra) and the ten point mean roughness (Rz) are obtained. The average roughness Ra values of several coatings vary from 0.3-17.69 microns. The average roughness Rz values of several coatings vary from 1.91-78.53 microns. For each plate, both the low and high coating thickness values were measured. The low values of the coating thickness varied from 17.5-147.5 microns. The high values of thickness vary from 35-185 microns. Details are provide in Table 25.

TABLE 25

Coating	Roughness Data (Microns)						AVG Ra	AVG Rz	STDEV	Coating Thickness Range (Low)	Coating Thickness Range (High)	Coating Thickness Range (Low)	Coating Thickness Range (High)
	T1	T2	T3	T4	T5	T6				Mils	Mils	Microns	Microns
Each Primer No Filler Ts-720													
Ra	0.848	0.032	0.258	0.094			0.31		0.37	0.7	1.4	17.5	35
Rz	5.33	0.23	1.4	0.67				191	233				
Bare Aluminum													
Ra	0.33	0.45	0.22	0.342			0.34		0.09	0	0		
Rz	2.27	2.66	1.35	2.76				2.26	0.64				
Polane 20% IM30k Glass Polane TS720													
Ra	0.589	0.046	0.354	0.934			0.48		0.38	3.3	4.6	82.5	115
3.67	0.281	2.21	5.21				2.84	2.10					
Etch Primer Only													
Ra	0.561	0.519	0.574	0.564	0.542		0.55		0.02	1	1.5	2.5	37.5
Rz	4.06	3.65	4.05	4.35	3.95			4.01	0.25				
Polane 20% 9400 Hymod Ts720													
Ra	0.49	0.083	1.334	0.441			0.59		0.53	2.2	5.5	5.5	137.5
Rz	2.82	0.43	6.41	2.89				3.14	2.46				
Polane Only													
Ra	0.62	0.611	0.492	0.66			\$0.60		0.07	1	1.5	2.5	37.5
Rz	2.66	2.24	2.2	3.61				2.6775	0.66				
10% IM30K Glass Polane TS720													
Ra	0.942	0.718	0.982	0.863			0.88		0.12	0.9	1.65	22.5	41.25
Rz	6.53	5.6	6.01	5.51				5.91	0.47				
Polane + 4% TS720 Ts720													
Ra	2.213	1.753	0.078	0.123			1.04		1.10	1.15	2	28.75	50
Rz	15	17	0.6	0.72				8.33	8.89				
Etch + 20% Hymod 9400D Ts720													
Ra	0.397	0.125	1.887	2.199			1.15		1.04	1.1	2.7	27.5	67.5
Rz	4.13	0.69	17.2	15.5				9.38	8.20				
Polane + 5% M5 TS720-													
Ra	1.396	1.12	0.913	1.297			1.18		0.21	2.1	3.9	52.5	97.5
Rz	6.84	7.36	5.8	6.78				6.70	0.65				
Polane No filler TS720													
Ra	1.287	1.434	1.616	1.873			1.55		0.25	1.8	2.4	4.5	60
Rz	7.13	9.09	11.6	9.61				9.36	1.84				



TABLE 25-continued

Coating	Roughness Data (Microns)						AVG Ra	AVG Rz	STDEV	Coating Thickness Range (Low)	Coating Thickness Range (High)	Coating Thickness Range (Low)	Coating Thickness Range (High)
	T1	T2	T3	T4	T5	T6				Mils	Mils	Microns	Microns
Polane 7001 Water Base nanogel													
Ra	1.555	1.706	1.899	2.627			1.95		0.47	1.05	13	26.25	32.5
Rz	10.7	19	14.7	13.8	16.9			15.02	3.15				
Etch + 4% M5 TS720													
Ra	1.486	2.771	1.624	2.009	2.373		2.05		0.53	1.35	26	33.75	65
Rz	10.7	19	14.7	13.8	16.9			15.02	3.15				
Etch + 4% Acematt400													
Ra	1.206	1.646	1.478	4.24			2.14		1.41	1.4	23	35	57.5
Rz	7.98	11.3	15.9	33.7				17.22	11.46				
Etch + 4% TS720 Ts720													
Ra	4.08	3.752	4.806	4.853			4.37		0.54	1.2	2	30	50
Rz	26.9	24.5	29.2	37.1				29.43	5.46				
S60 Polane M5 Hex SiC148174													
Ra	6.6011	6.097	7.985	7.61			7.07		0.87	1.75	3.3	43.75	82.5
Rz	26	29.5	33.1	27.5									
Wood 140 Mo polane M5/Hex 8174 sic14													
Ra	7.32	8.476	6.436	8.579			7.70		1.02	4.1	5.1	102.5	127.5
Rz	35.8	41.6	31.8	43.7				38.23	5.43				
Corvel Black M-5 8174													
Ra	9.027	8.481	9.929	8.05			8.87		0.81	5.9	7.4	147.5	185
Rz	49.1	48.9	62.7	42.9				50.90	8.38				
512 W polane M-5/hex Sic148474													
Ra	11.01	12.48	13	14.17			12.67		1.31	3.9	5.2	97.5	130
Rz	68	77.9	74.7	86.1				76.68	7.52				
512 B Polane M-5 Hex Sic148174													
Ra	17.64	17.64	18.03	14.95	18.61	19.24	17.69		1.47	5.5	6.9	137.5	172.5
Rz	86.9	75.3	70.4	70.4	71.2	97		78.53	11.02				

## Example 26

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TABLE 26

## Baseline Contact Angles for Three Binder Systems

Aluminum plates, 4 inches×4 inches, are coated with one of three different binders in the absence of any added first or second particles. After curing at 200° F. for 30-60 min, contact angle for each of the plates with water at about 18 to about 22° C. is measured. The results indicate the following contact angles are found for the binders.

Self Etching Primer: Contact angle varies from 80.69-83.27°.

Polane B: Contact angle varies from 69.39-71.3°.

Lumiflon: Contact angle varies from 75.76-80.70°.

Details are provided in Table 26.

Contact Angle for Water Coatings Employing Three Binder Systems

Plate	Contact Angle Left	Contact Angle Right	Volume (uL)	Average (°)
55 Etch Primer	80.32	81.05	3.21	80.69
Etch Primer	82.60	83.47	3.21	83.04
Etch Primer	83.56	82.98	3.14	83.27
60 Polane	70.93	71.67	3.51	71.30
Polane	69.97	70.00	4.00	69.99
Polane	69.74	69.03	3.03	69.39
Lumiflon	76.00	75.51	2.61	75.76
Lumiflon	77.54	78.71	2.52	78.13
65 Lumiflon	80.11	81.28	2.46	80.70

Plates were also tested for roll-off angle, in each case the binders have roll-off angles greater than 60 and less than 90 degrees and leave residual water on the surface.

### Example 27

#### Fabrics With Durable Hydrophobic Properties

Fabric samples are treated with a silanizing agent alone, or with either  $\text{SiCl}_4$  or  $\text{Si}(\text{OEt})_4$  followed by treatment with a silanizing agent, as indicated in Table 26. Two different silanizing agents were employed, (tridecafluoro-1,1,2,2-tetrahydrooctyl)trichlorosilane, which is a fluorinated silane, and n-octadecyltrichlorosilane, which is a not fluorinated. The treatment process comprised applying 10% solutions of either  $\text{SiCl}_4$  or  $\text{Si}(\text{OEt})_4$  in hexane, or combinations thereof, to fabric samples by brushing the solutions on the fabric. Following treatment with  $\text{SiCl}_4$  or  $\text{Si}(\text{OEt})_4$  the fabric is cured at about 93° C. (about 200° F.) for 60 minutes (min). Silanes are then brushed on the fabric as a 1% solution in hexane, and the fabric samples are again cured at about 93° C. (about 200° F.) for 60 min. Where acetic acid is employed it is used as a

catalyst. Ten different fabrics having a variety of compositions are treated in this manner.

As an alternative to applying the agents by brushing, either the  $\text{SiCl}_4$  or  $\text{Si}(\text{OEt})_4$ , can also be applied by immersing the fabric in 10% solution of those agents in hexane under a pressure of 20 psi (pound per square inch) for 5 min. This step was carried out to enhance the attachment of  $\text{SiCl}_4$  or  $\text{Si}(\text{OEt})_4$  to the fabrics.

Hydrophobicity of the fabrics is observed by observing the beading and non-wetting behavior of the fabric samples. The durability of the hydrophobicity is measured by washing in soapy water until non-wetting performance ends. Four different commercial detergents, Ajax, Dawn, Tide, and Tide with 5% bleach are employed for the washing, which used the detergents in the amounts indicated by the suppliers. After each wash fabric samples are dried at about 93° C. (about 200° F.) for 15 min.

The data for each fabric sample's response to washing are presented in Table 27. Those data suggest that significant hydrophobicity, with resistance to washing, can be introduced into fabrics.

TABLE 27

Treatment Data for Fabrics						
fabric	initial Si treatment	silane treatment	wash cycles to failure	soap used	Process ID	
nylon (yellow)	$\text{SiCl}_4$	8174	8	Ajax	Ross F1	
nylon (blue)	$\text{SiCl}_4$	8174	5	Ajax	Ross F1	
nylon (orange)	$\text{SiCl}_4$	8174	5	Ajax	Ross F1	
army fabric	$\text{SiCl}_4$	8174	3	Ajax	Ross F1	
polyester	$\text{SiCl}_4$	8174	5	Ajax	Ross F1	
acetate	$\text{SiCl}_4$	8174	12	Ajax	Ross F1	
velvet	$\text{SiCl}_4$	8174	3	Ajax	Ross F1	
vinyl	$\text{SiCl}_4$	8174	1	Ajax	Ross F1	
Cotton			0		Ross F1	
nylon (yellow)	$(\text{SiO})_x(\text{OEt})_3$	8174	4	Ajax	Ross F2	
nylon (blue)	$(\text{SiO})_x(\text{OEt})_3$	8174	5	Ajax	Ross F2	
nylon (orange)	$(\text{SiO})_x(\text{OEt})_3$	8174	5	Ajax	Ross F2	
army fabric	$(\text{SiO})_x(\text{OEt})_3$	8174	4	Ajax	Ross F2	
polyester	$(\text{SiO})_x(\text{OEt})_3$	8174	3	Ajax	Ross F2	
acetate	$(\text{SiO})_x(\text{OEt})_3$	8174	8	Ajax	Ross F2	
velvet	$(\text{SiO})_x(\text{OEt})_3$	8174	1	Ajax	Ross F2	
vinyl	$(\text{SiO})_x(\text{OEt})_3$	8174	1	Ajax	Ross F2	
Cotton			0		Ross F2	
nylon (yellow)	$\text{Si}(\text{EtO})_4$	8174	9	Ajax	Ross F3	
nylon (blue)	$\text{Si}(\text{EtO})_4$	8174	9	Ajax	Ross F3	
nylon (orange)	$\text{Si}(\text{EtO})_4$	8174	9	Ajax	Ross F3	
army fabric	$\text{Si}(\text{EtO})_4$	8174	2	Ajax	Ross F3	
polyester	$\text{Si}(\text{EtO})_4$	8174	4	Ajax	Ross F3	
acetate	$\text{Si}(\text{EtO})_4$	8174	10	Ajax	Ross F3	
velvet	$\text{Si}(\text{EtO})_4$	8174	1	Ajax	Ross F3	
vinyl	$\text{Si}(\text{EtO})_4$	8174	1	Ajax	Ross F3	
Cotton			0		Ross F3	
nylon (yellow)	none	8174	12	Ajax	Ross F4	
nylon (blue)	none	8174	4	Ajax	Ross F4	
nylon (orange)	none	8174	12	Ajax	Ross F4	
army fabric	none	8174	1	Ajax	Ross F4	
polyester	none	8174	2	Ajax	Ross F4	
acetate	none	8174	4	Ajax	Ross F4	
velvet	none	8174	1	Ajax	Ross F4	
vinyl	none	8174	1	Ajax	Ross F4	
Cotton			0		Ross F4	
nylon (yellow)	$\text{SiCl}_4$	6640	6	Ajax	Ross F5	
nylon (blue)	$\text{SiCl}_4$	6640	6	Ajax	Ross F5	
nylon (orange)	$\text{SiCl}_4$	6640	4	Ajax	Ross F5	
army fabric	$\text{SiCl}_4$	6640	1	Ajax	Ross F5	
polyester	$\text{SiCl}_4$	6640	2	Ajax	Ross F5	
acetate	$\text{SiCl}_4$	6640	4	Ajax	Ross F5	
velvet	$\text{SiCl}_4$	6640	1	Ajax	Ross F5	
vinyl	$\text{SiCl}_4$	6640	1	Ajax	Ross F5	
cotton	$\text{SiCl}_4$	6640	1	Ajax	Ross F5	
nylon (yellow)	Di oil based (soaked for 5 min.)	none	2	Ajax	Ross DF1	
nylon (blue)	Di oil based (soaked for 5 min.)	none	0	Ajax	Ross DF1	dead at start
nylon (orange)	Di oil based (soaked for 5 min.)	none	0	Ajax	Ross DF1	dead at start

TABLE 27-continued

Treatment Data for Fabrics						
fabric	initial Si treatment	silane treatment	wash cycles to failure	soap used	Process ID	
army fabric	Di oil based (soaked for 5 min.)	none	0	Ajax	Ross DF1	dead at start
polyester	Di oil based (soaked for 5 min.)	none	1	Ajax	Ross DF1	
acetate	Di oil based (soaked for 5 min.)	none	0	Ajax	Ross DF1	dead at start
velvet	Di oil based (soaked for 5 min.)	none	0	Ajax	Ross DF1	dead at start
vinyl	Di oil based (soaked for 5 min.)	none	0	Ajax	Ross DF1	dead at start
cotton	Di oil based (soaked for 5 min.)	none	0	Ajax	Ross DF1	dead at start
white fabric	Di oil based (soaked for 5 min.)	none	0	Ajax	Ross DF1	dead at start
nylon (yellow)	Di water based (soaked for 10 min.)	none	1	Ajax	Ross DF2	
nylon (blue)	Di water based (soaked for 10 min.)	none	0	Ajax	Ross DF2	dead at start
nylon (orange)	Di water based (soaked for 10 min.)	none	0	Ajax	Ross DF2	dead at start
army fabric	Di water based (soaked for 10 min.)	none	0	Ajax	Ross DF2	dead at start
polyester	Di water based (soaked for 10 min.)	none	0	Ajax	Ross DF2	dead at start
acetate	Di water based (soaked for 10 min.)	none	0	Ajax	Ross DF2	dead at start
velvet	Di water based (soaked for 10 min.)	none	0	Ajax	Ross DF2	dead at start
vinyl	Di water based (soaked for 10 min.)	none	1	Ajax	Ross DF2	
cotton	Di water based (soaked for 10 min.)	none	0	Ajax	Ross DF2	dead at start
white fabric	Di water based (soaked for 10 min.)	none	0	Ajax	Ross DF2	dead at start
nylon (yellow)	Di oil based pressurized at 20 psi for 5 min.	none	3	Ajax	Ross DF3	
nylon (blue)	Di oil based pressurized at 20 psi for 5 min.	none	0	Ajax	Ross DF3	dead at start
nylon (orange)	Di oil based pressurized at 20 psi for 5 min.	none	2	Ajax	Ross DF3	
army fabric	Di oil based pressurized at 20 psi for 5 min.	none	0	Ajax	Ross DF3	dead at start
polyester	Di oil based pressurized at 20 psi for 5 min.	none	2	Ajax	Ross DF3	
acetate	Di oil based pressurized at 20 psi for 5 min.	none	0	Ajax	Ross DF3	dead at start
velvet	Di oil based pressurized at 20 psi for 5 min.	none	0	Ajax	Ross DF3	dead at start
vinyl	Di oil based pressurized at 20 psi for 5 min.	none	0	Ajax	Ross DF3	dead at start
cotton	Di oil based pressurized at 20 psi for 5 min.	none	0	Ajax	Ross DF3	dead at start
white fabric	Di oil based pressurized at 20 psi for 5 min.	none	0	Ajax	Ross DF3	dead at start
nylon (yellow)	pressurized SiCl <sub>4</sub> at 20 psi for 5 min.	8174	7	Ajax	Ross F6	
nylon (blue)	pressurized SiCl <sub>4</sub> at 20 psi for 5 min.	8174	18	Ajax	Ross F6	
nylon (orange)	pressurized SiCl <sub>4</sub> at 20 psi for 5 min.	8174	19	Ajax	Ross F6	
army fabric	pressurized SiCl <sub>4</sub> at 20 psi for 5 min.	8174	3	Ajax	Ross F6	
polyester	pressurized SiCl <sub>4</sub> at 20 psi for 5 min.	8174	6	Ajax	Ross F6	
acetate	pressurized SiCl <sub>4</sub> at 20 psi for 5 min.	8174	18	Ajax	Ross F6	
velvet	pressurized SiCl <sub>4</sub> at 20 psi for 5 min.	8174	1	Ajax	Ross F6	
vinyl	pressurized SiCl <sub>4</sub> at 20 psi for 5 min.	8174	5	Ajax	Ross F6	
cotton	pressurized SiCl <sub>4</sub> at 20 psi for 5 min.	8174	16	Ajax	Ross F6	16 (tore apart)
white fabric	pressurized SiCl <sub>4</sub> at 20 psi for 5 min.	8174	3	Ajax	Ross F6	
nylon (yellow)	Si(EtO) <sub>4</sub> pressurized at 20 psi for 5 min.	8174	35	Dawn	Ross F7	
nylon (blue)	Si(EtO) <sub>4</sub> pressurized at 20 psi for 5 min.	8174	30	Dawn	Ross F7	
nylon (orange)	Si(EtO) <sub>4</sub> pressurized at 20 psi for 5 min.	8174	30	Dawn	Ross F7	
army fabric	Si(EtO) <sub>4</sub> pressurized at 20 psi for 5 min.	8174	2	Dawn	Ross F7	
polyester	Si(EtO) <sub>4</sub> pressurized at 20 psi for 5 min.	8174	35	Dawn	Ross F7	
acetate	Si(EtO) <sub>4</sub> pressurized at 20 psi for 5 min.	8174	30	Dawn	Ross F7	
velvet	Si(EtO) <sub>4</sub> pressurized at 20 psi for 5 min.	8174	dead at start	Dawn	Ross F7	
vinyl	Si(EtO) <sub>4</sub> pressurized at 20 psi for 5 min.	8174	25	Dawn	Ross F7	
cotton	Si(EtO) <sub>4</sub> pressurized at 20 psi for 5 min.	8174	15	Dawn	Ross F7	
white fabric	Si(EtO) <sub>4</sub> pressurized at 20 psi for 5 min.	8174	dead at start	Dawn	Ross F7	
nylon (yellow)	Si(EtO) <sub>4</sub> with acetic acid	8174	8	Tide	Ross F8	
nylon (blue)	Si(EtO) <sub>4</sub> with acetic acid	8174	3	Tide	Ross F8	
nylon (orange)	Si(EtO) <sub>4</sub> with acetic acid	8174	7	Tide	Ross F8	
army fabric	Si(EtO) <sub>4</sub> with acetic acid	8174	1	Tide	Ross F8	
polyester	Si(EtO) <sub>4</sub> with acetic acid	8174	4	Tide	Ross F8	
acetate	Si(EtO) <sub>4</sub> with acetic acid	8174	0	Tide	Ross F8	dead at start
velvet	Si(EtO) <sub>4</sub> with acetic acid	8174	1	Tide	Ross F8	
vinyl	Si(EtO) <sub>4</sub> with acetic acid	8174	9	Tide	Ross F8	
cotton	Si(EtO) <sub>4</sub> with acetic acid	8174	0	Tide	Ross F8	dead at start
white fabric	Si(EtO) <sub>4</sub> with acetic acid	8174	2	Tide	Ross F8	
nylon (yellow)	Si(EtO) <sub>4</sub> with acetic acid	6640	10	Tide	Ross F9	
nylon (blue)	Si(EtO) <sub>4</sub> with acetic acid	6640	4	Tide	Ross F9	
nylon (orange)	Si(EtO) <sub>4</sub> with acetic acid	6640	9	Tide	Ross F9	
army fabric	Si(EtO) <sub>4</sub> with acetic acid	6640	4	Tide	Ross F9	
polyester	Si(EtO) <sub>4</sub> with acetic acid	6640	5	Tide	Ross F9	
acetate	Si(EtO) <sub>4</sub> with acetic acid	6640	1	Tide	Ross F9	
velvet	Si(EtO) <sub>4</sub> with acetic acid	6640	1	Tide	Ross F9	
vinyl	Si(EtO) <sub>4</sub> with acetic acid	6640	9	Tide	Ross F9	
cotton	Si(EtO) <sub>4</sub> with acetic acid	6640	1	Tide	Ross F9	
white fabric	Si(EtO) <sub>4</sub> with acetic acid	6640	5	Tide	Ross F9	
nylon (yellow)	SiCl <sub>4</sub>	8174	10	Tide	Ross F10	
nylon (blue)	SiCl <sub>4</sub>	8174	18	Tide	Ross F10	
nylon (orange)	SiCl <sub>4</sub>	8174	38	Tide	Ross F10	
army fabric	SiCl <sub>4</sub>	8174	4	Tide	Ross F10	
polyester	SiCl <sub>4</sub>	8174	3	Tide	Ross F10	
acetate	SiCl <sub>4</sub>	8174	45	Tide	Ross F10	
velvet	SiCl <sub>4</sub>	8174	2	Tide	Ross F10	
vinyl	SiCl <sub>4</sub>	8174	3	Tide	Ross F10	
cotton	SiCl <sub>4</sub>	8174	40	Tide	Ross F10	Tore Apart

TABLE 27-continued

Treatment Data for Fabrics					
fabric	initial Si treatment	silane treatment	wash cycles to failure	soap used	Process ID
white fabric	SiCl <sub>4</sub>	8174	1	Tide	Ross F10
nylon (yellow)	Si(EtO) <sub>4</sub> with acetic acid pressurized at 20 psi	6640	12	Tide	Ross F11
nylon (blue)	Si(EtO) <sub>4</sub> with acetic acid pressurized at 20 psi	6640	0	Tide	Ross F11
nylon (orange)	Si(EtO) <sub>4</sub> with acetic acid pressurized at 20 psi	6640	10	Tide	Ross F11
army fabric	Si(EtO) <sub>4</sub> with acetic acid pressurized at 20 psi	6640	1	Tide	Ross F11
polyester	Si(EtO) <sub>4</sub> with acetic acid pressurized at 20 psi	6640	0	Tide	Ross F11
acetate	Si(EtO) <sub>4</sub> with acetic acid pressurized at 20 psi	6640	1	Tide	Ross F11
velvet	Si(EtO) <sub>4</sub> with acetic acid pressurized at 20 psi	6640	0	Tide	Ross F11
vinyl	Si(EtO) <sub>4</sub> with acetic acid pressurized at 20 psi	6640	15	Tide	Ross F11
cotton	Si(EtO) <sub>4</sub> with acetic acid pressurized at 20 psi	6640	0	Tide	Ross F11
white fabric	Si(EtO) <sub>4</sub> with acetic acid pressurized at 20 psi	6640	0	Tide	Ross F11
nylon (yellow)	SiCl <sub>4</sub>	8174		Tide with 5%	Ross F12
nylon (blue)	SiCl <sub>4</sub>	8174		Tide with 5%	Ross F12
nylon (orange)	SiCl <sub>4</sub>	8174		Tide with 5%	Ross F12
army fabric	SiCl <sub>4</sub>	8174	4	Tide with 5%	Ross F12
polyester	SiCl <sub>4</sub>	8174	3	Tide with 5%	Ross F12
acetate	SiCl <sub>4</sub>	8174		Tide with 5%	Ross F12
velvet	SiCl <sub>4</sub>	8174	0	Tide with 5%	Ross F12
vinyl	SiCl <sub>4</sub>	8174	4	Tide with 5%	Ross F12
cotton	SiCl <sub>4</sub>	8174		Tide with 5%	Ross F12
white fabric	SiCl <sub>4</sub>	8174	1	Tide with 5%	Ross F12

The invention claimed is:

1. A hydrophobic coating on a substrate prepared by a method comprising:

a) applying to said substrate a coating composition, comprising i) a binder, ii) first particles having a size of about 30 microns to about 225 microns, and iii) a solvent, to provide a base coating; and

b)

applying to said base coating a composition comprising second particles having a size of about 1 nanometer to 25 microns, wherein, prior to the application of the second particles to the base coating,

i) the second particles have been modified with hexamethyldisilazane,

ii) the second particles comprise covalently bound polydimethylsiloxane, or

iii) the second particles comprise one or more covalently bound moieties independently selected from the group consisting of alkyl, haloalkyl and perfluoroalkyl moieties, which one or more moieties are covalently bound to said second particles by reaction of the particles with a silanizing agent of formula (I), said compound of formula (I) having the structure:



where n is an integer from 1 to 3;

each R is independently selected from

(i) C<sub>1 to 20</sub> alkyl optionally substituted with one or more fluorine atoms; or

(ii) —Z—((CF<sub>2</sub>)<sub>q</sub>(CF<sub>3</sub>))<sub>r</sub>, wherein Z is a C<sub>1-12</sub> divalent alkane radical or a C<sub>2-12</sub> divalent alkene or alkyne radical, q is an integer from 1 to 12, and r is an integer from 1-4;

each X is independently selected from the group consisting of —H, —Cl, —I, —Br, —OH, —OR<sup>2</sup>, —NHR<sup>3</sup>, and —N(R<sup>3</sup>)<sub>2</sub>;

each R<sup>2</sup> is an independently selected C<sub>1 to 4</sub> alkyl or haloalkyl group; and

each R<sup>3</sup> is an independently selected H, C<sub>1 to 4</sub> alkyl or haloalkyl group;

wherein said coating has a contact angle with water that is greater than about 120° at a temperature of 18° C. to 23° C.;

wherein the coating has a surface in contact with the substrate and an exposed surface comprising the binder that is not in contact with the substrate, the exposed surface having an arithmetical mean roughness from about 0.2 microns to about 20 microns, or a ten point mean roughness from about 1 micron to about 90 microns;

wherein, in the resulting coating, the first particles are primarily distributed within and coated with the binder and the second particles are primarily distributed on the exposed surface;

and

wherein the coating has a greater number of second particles on the exposed surface than on the surface in contact with the substrate.

2. The coating of claim 1, wherein the binder comprises a polyurethane, lacquer, fluoropolymer, epoxy or thermoplastic powder coating.

3. The coating of claim 1, wherein said first particles comprise a material selected from the group consisting of: wood, cellulose, metal oxides, metalloid oxides, plastics, carbides, nitrides, borides, spinels, diamonds, fibers, thermoplastics and glass.

4. The coating of claim 1, wherein said second particles comprise: a metal oxide, an oxide of a metalloid, a silicate, or a glass.

5. The coating of claim 1, wherein said second particles comprise one or more fluoroalkyl or perfluoroalkyl moieties that are covalently bound to the second particles directly or indirectly through one or more atoms bound to the second particles.

6. The coating of claim 1, wherein, prior to the application of the second particles to the base coating, said second particles have been modified with an agent selected from the group consisting of: (tridecafluoro-1,1,2,2-tetrahydrooctyl) silane; (tridecafluoro-1,1,2,2-tetrahydrooctyl) trichlorosilane; (tridecafluoro-1,1,2,2-tetrahydrooctyl)triethoxysilane; (tridecafluoro-1,1,2,2-tetrahydrooctyl)trimethoxysilane; (heptadecafluoro-1,1,2,2-tetrahydrodecyl)dimethyl(dimethylamino)silane; (heptadecafluoro-1,1,2,2-tetrahydrodecyl)tris(dimethylamino)silane; n-octadecyltrimethoxysilane; n-octyltriethoxysilane; nonafluorohexyldimethyl(dimethylamino)silane, and polydimethylsiloxane; and

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wherein, following the modification, the second particles comprise at least one moiety selected from the group consisting of alkyl, haloalkyl, and perfluoroalkyl.

7. The hydrophobic coating of claim 1, wherein the hydrophobic coating has an arithmetical mean roughness from about 0.2 microns to about 20 microns.

8. The hydrophobic coating of claim 1, wherein said hydrophobic coating retains its hydrophobicity when subject to at least 200 abrasion cycles, as measured with a Taber Abrasion tester model 503 using CS-10 wheels and 250 g loads, wherein a surface is no longer considered to retain its hydrophobicity when more than half of the water droplets placed on the abraded surface are retained on the abraded surface if the surface is inclined at an angle of 6°.

9. The hydrophobic coating of claim 1, wherein said coating has a contact angle with water that is greater than about 130° at 18° C. to 23° C.

10. A system for applying a hydrophobic coating on a substrate, the system comprising as separate components component (a) and component (b);

wherein component (a) for application of a base coating comprises i) a binder, ii) a solvent, and iii) first particles having a size of about 30 microns to about 225 microns, and wherein said component (b) comprises second particles having a size of about 1 nanometer to 25 microns, where, prior to the application of the second particles to the base coating,

- i) the second particles have been modified with hexamethyldisilazane,
- ii) the second particles comprise covalently bound polydimethylsiloxane, or
- iii) the second particles comprise one or more covalently bound moieties independently selected from the group consisting of alkyl, haloalkyl, and perfluoroalkyl moieties, which one or more moieties are covalently bound to said second particles by reaction of the particles with a silanizing agent of formula (I), said compound of formula (I) having the structure:



where n is an integer from 1 to 3;

each R is independently selected from

(i) C<sub>1 to 20</sub> alkyl optionally substituted with one or more fluorine atoms; or

(ii) —Z—((CF<sub>2</sub>)<sub>q</sub>(CF<sub>3</sub>))<sub>r</sub>, wherein Z is a C<sub>1-12</sub> divalent alkane radical or a C<sub>2-12</sub> divalent alkene or alkyne radical, q is an integer from 1 to 12, and r is an integer from 1-4;

each X is independently selected from the group consisting of —H, —Cl, —I, —Br, —OH, —OR<sup>2</sup>, —NHR<sup>3</sup>, and —N(R<sup>3</sup>)<sub>2</sub>;

each R<sup>2</sup> is an independently selected C<sub>1 to 4</sub> alkyl or haloalkyl group; and

each R<sup>3</sup> is an independently selected H, C<sub>1 to 4</sub> alkyl or haloalkyl group;

wherein the composition of component (a) and component (b) are such that application of component (a) to the substrate to form a base coat comprised of the binder and first particles followed by application of component (b) to said base coat produces the hydrophobic coating on said substrate, the hydrophobic coating having a surface in contact with the substrate and an exposed surface comprising the binder;

wherein, in the resulting hydrophobic coating, the first particles are primarily distributed within and coated with the binder, and the second particles are primarily distributed on the exposed surface; and

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wherein the hydrophobic coating has an arithmetical mean roughness from about 0.2 microns to about 20 microns or a ten point mean roughness from about 1 micron to about 90 microns.

11. The system of claim 10, wherein said first particles comprise a plastic.

12. The system of claim 11, wherein said first particles are hollow spheres.

13. The system of claim 10, wherein said second particles have been modified with a silanizing agent of formula (I):



where n is an integer from 1 to 3;

each R is an independently selected C<sub>1 to 20</sub> alkyl optionally substituted with one or more fluorine atoms;

each X is independently selected from the group consisting of —H, —Cl, —I, —Br, —OH, —OR<sup>2</sup>, —NHR<sup>3</sup>, and —N(R<sup>3</sup>)<sub>2</sub>;

each R<sup>2</sup> is an independently selected C<sub>1 to 4</sub> alkyl or haloalkyl group; and

each R<sup>3</sup> is an independently selected H, C<sub>1 to 4</sub> alkyl or haloalkyl group.

14. A dried and cured hydrophobic coating applied to a substrate, wherein the coating has a surface in contact with said substrate and an exposed surface comprising binder that is not in contact with the substrate, the coating comprising:

i) a binder; ii) first particles having a size of about 30 microns to about 225 microns; and

iii) second particles having a size of about 1 nanometer to 25 microns that have been modified with hexamethyldisilazane, comprise covalently bound polydimethylsiloxane, or comprise one or more covalently bound moieties independently selected from the group consisting of alkyl, haloalkyl and perfluoroalkyl;

wherein the coating optionally contains 5% to 10% of a block copolymer on a weight basis, the exposed surface having an arithmetical mean roughness from about 0.2 microns to about 20 microns or a ten point mean roughness from about 1 micron to about 90 microns;

wherein said coating has a contact angle with water that is greater than about 120° at a temperature of 18° C. to 23° C.;

wherein, in the hydrophobic coating, the first particles are primarily distributed within and coated with the binder, and the second particles are primarily distributed on the exposed surface; and

wherein the coating has a greater number of second particles on the exposed surface than on the surface in contact with the substrate.

15. The coating of claim 14, wherein the coating comprises first particles in a range from about 2% to about 40% on a weight basis.

16. The coating of claim 14, wherein the coating comprises second particles in a range selected from about 1% to about 10% on a weight basis.

17. The coating of claim 14, wherein the binder comprises a polyurethane, lacquer, fluoropolymer, epoxy or thermoplastic powder coating.

18. The hydrophobic coating of claim 14, wherein the coating retains its hydrophobicity when subject to at least 200 abrasion cycles, as measured with a Taber Abrasion tester model 503 using CS-10 wheels and 250 g loads, wherein a surface is no longer considered to retain its hydrophobicity when more than half of the water droplets placed on the abraded surface are retained on the abraded surface if the surface is inclined at an angle of 6°.

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19. The coating of claim 18, wherein said binder comprises a polyurethane.

20. The coating of claim 18, wherein the coating retains its hydrophobicity when subject to at least 300 abrasion cycles, as measured with a Taber Abrasion tester model 503 using CS-10 wheels and 250 g loads, wherein a surface is no longer considered to retain its hydrophobicity when more than half of the water droplets placed on the abraded surface are retained on the abraded surface if the surface is inclined at an angle of 6°.

21. A hydrophobic coating on a substrate prepared by a method comprising:

a) applying to said substrate a coating composition comprising i) a binder, ii) a solvent, and iii) first particles having a size of about 30 micron to about 225 microns, to provide a base coating;

b) applying to said base coating a composition comprising a solvent and second particles comprised of silica or alumina having a size of about 1 nanometer to 25 microns, wherein prior to the application of said second particles to said base coating

i) the second particles have been modified with hexamethyldisilazane,

ii) the second particles comprise covalently bound polydimethylsiloxane, or

iii) the second particles comprise one or more covalently bound moieties independently selected from the group consisting of alkyl, haloalkyl and perfluoroalkyl moieties, which one or more moieties are covalently bound to said second particles by reaction of the particles with a silanizing agent of formula (I), said compound of formula (I) having the structure:



where n is an integer from 1 to 3;

each R is an independently selected  $C_{1 \text{ to } 20}$  alkyl optionally substituted with one or more fluorine atoms, or each R is a  $-Z-((CF_2)_q(CF_3))_r$  group, wherein Z is a  $C_{1-12}$  divalent alkane, q is an integer from 1 to 12, and r is an integer from 1-4;

each X is independently selected from the group consisting of  $-H$ ,  $-Cl$ ,  $-I$ ,  $-Br$ ,  $-OH$ ,  $-OR^2$ ,  $-NHR^3$ , and  $-N(R^3)_2$ ;

each  $R^2$  is an independently selected  $C_{1 \text{ to } 4}$  alkyl or haloalkyl group; and

each  $R^3$  is an independently selected  $H$ ,  $C_{1 \text{ to } 4}$  alkyl or haloalkyl group;

wherein the coating has a surface in contact with the substrate and an exposed surface comprising the binder that is not in contact with the substrate, the exposed surface having an arithmetical mean roughness from about 0.2 microns to about 20 microns, or a ten point mean roughness from about 1 micron to about 90 microns;

wherein said coating has a contact angle with water that is greater than about 120° at a temperature of 18° C. to 23° C.; wherein, in the resulting hydrophobic coating, the first particles are primarily distributed within and coated with the binder, and the second particles are primarily distributed on the exposed surface;

and

wherein the coating has a greater number of second particles on the exposed surface than on the surface in contact with the substrate.

22. The coating of claim 21, wherein said second particles are second particles that have been modified with hexamethyldisilazane, octyltrimethoxysilane, polydimethylsiloxane, or tridecafluoro-1,1,2,2-tetrahydrooctyl trichlorosilane.

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23. The coating according to claim 21, wherein the contact angle with water is greater than about 130°.

24. The coating of claim 23, wherein the coating retains its hydrophobicity when subject to at least 100 abrasion cycles, as measured with a Taber Abrasion tester model 503 using CS-10 wheels and 250 g loads, wherein a surface is no longer considered to retain its hydrophobicity when more than half of the water droplets placed on the abraded surface are retained on the abraded surface if the surface is inclined at an angle of 6°.

25. The coating according to claim 24, wherein the contact angle with water is greater than about 150°.

26. The hydrophobic coating of claim 1, wherein said second particles that comprise one or more covalently bound moieties independently selected from the group consisting of alkyl, haloalkyl and perfluoroalkyl moieties are second particles that have been modified with a silanizing agent of formula (I):



where n is an integer from 1 to 3;

each R is an independently selected  $-Z-((CF_2)_q(CF_3))_r$  group, wherein Z is a  $C_{1-12}$  divalent alkane, q is an integer from 1 to 12, and r is an integer from 1-4;

each X is independently selected from the group consisting of  $-H$ ,  $-Cl$ ,  $-I$ ,  $-Br$ ,  $-OH$ ,  $-OR^2$ ,  $-NHR^3$ , and  $-N(R^3)_2$ ;

each  $R^2$  is an independently selected  $C_{1 \text{ to } 4}$  alkyl or haloalkyl group; and

each  $R^3$  is an independently selected  $H$ ,  $C_{1 \text{ to } 4}$  alkyl or haloalkyl group.

27. The coating of claim 1, wherein said coating has a contact angle with water that is greater than about 140° at 18° C. to 23° C.

28. The coating of claim 14, wherein said second particles that comprise one or more independently selected alkyl, haloalkyl or perfluoroalkyl moieties covalently bound are second particles that have been modified with a silanizing agent of formula (I):



where n is an integer from 1 to 3;

each R is an independently selected  $-Z-((CF_2)_q(CF_3))_r$  group, wherein Z is a  $C_{1-12}$  divalent alkane radical, q is an integer from 1 to 12, and r is an integer from 1-4;

each X is independently selected from the group consisting of  $-H$ ,  $-Cl$ ,  $-I$ ,  $-Br$ ,  $-OH$ ,  $-OR^2$ ,  $-NHR^3$ , and  $-N(R^3)_2$ ;

each  $R^2$  is an independently selected  $C_{1 \text{ to } 4}$  alkyl or haloalkyl group; and

each  $R^3$  is an independently selected  $H$ ,  $C_{1 \text{ to } 4}$  alkyl or haloalkyl group.

29. The coating of claim 21, wherein said second particles that comprise one or more independently selected alkyl, haloalkyl or perfluoroalkyl moieties covalently bound are second particles that have been modified with a silanizing agent of formula (I):



where n is an integer from 1 to 3;

each R is an independently selected  $-Z-((CF_2)_q(CF_3))_r$  group, wherein Z is a  $C_{1-12}$  divalent alkane radical, q is an integer from 1 to 12, and r is an integer from 1-4;

each X is independently selected from the group consisting of  $-H$ ,  $-Cl$ ,  $-I$ ,  $-Br$ ,  $-OH$ ,  $-OR^2$ ,  $-NHR^3$ , and  $-N(R^3)_2$ ;

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each  $R^2$  is an independently selected  $C_{1 \text{ to } 4}$  alkyl or haloalkyl group; and  
 each  $R^3$  is an independently selected H,  $C_{1 \text{ to } 4}$  alkyl or haloalkyl group.

30. A system for applying a hydrophobic coating on a substrate, the system comprising as separate components component (a) and component (b);

wherein component (a) for application of a base coating comprises i) a binder, ii) a solvent, and iii) first particles having a size of about 30 microns to about 225 microns, wherein said component (a) optionally comprises one or more solvents; and

wherein component (b) comprises silica or alumina second particles having a size of about 1 nanometer to 25 microns, where, prior to the application of the second particles to the base coating,

- i) the second particles have been modified with hexamethyldisilazane,
- ii) the second particles comprise covalently bound polydimethylsiloxane, or
- iii) the second particles comprise one or more covalently bound moieties independently selected from the group consisting of alkyl, haloalkyl and perfluoroalkyl moieties, are covalently bound to said second particles by reaction of the particles with a silanizing agent of formula (I), said compound of formula (I) having the structure:



where n is an integer from 1 to 3;

each R is independently selected from

- (i)  $C_{1 \text{ to } 20}$  alkyl optionally substituted with one or more fluorine atoms; and

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- (ii)  $-Z-((CF_2)_q(CF_3))_r^r$ , wherein Z is a  $C_{1-12}$  divalent alkane radical or a  $C_{2-12}$  divalent alkene or alkyne radical, q is an integer from 1 to 12, and r is an integer from 1-4;

each X is independently selected from the group consisting of  $-Cl$ ,  $-OR^2$ ,  $-NHR^3$ , and  $-N(R^3)_2$ ;

each  $R^2$  is an independently selected  $C_{1 \text{ to } 4}$  alkyl or haloalkyl group; and

each  $R^3$  is an independently selected H,  $C_{1 \text{ to } 4}$  alkyl or haloalkyl group;

wherein the composition of component (a) and component (b) are such that application of component (a) to the substrate to form a base coat comprised of the binder and first particles followed by application of component (b) to said base coat produces the hydrophobic coating on said substrate, the hydrophobic coating having a surface in contact with the substrate and an exposed surface comprising the binder;

wherein, in the resulting hydrophobic coating, the first particles are primarily distributed within and coated with the binder, and the second particles are primarily distributed on the exposed surface; and

wherein the hydrophobic coating has an arithmetical mean roughness from about 0.2 microns to about 20 microns or a ten point mean roughness from about 1 micron to about 90 microns and a contact angle with water that is greater than about  $160^\circ$  at a temperature of  $18^\circ C.$  to  $23^\circ C.$

31. The coating of claim 1, wherein said contact angle with water is greater than about  $150^\circ$ .

32. The coating of claim 1, wherein said contact angle with water is greater than about  $160^\circ$ .

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